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30-CM ION THRUSTER POWER PROCESSOR

Final Report

Contract NAS3-17223

April 1978

By

Ion Physics Department Staff
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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
NASA Lewis Research Center

James S. Sovey, Program Manager



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16. Abstract <p>The weight, efficiency, reliability, and cost of the power processing unit needed to power and control an ion thruster are recognized as major contributors to the characterization of the total thrust subsystem. The power processor performance factors strongly influence the results of Solar Electric Propulsion (SEP) mission analysis; in many cases, these factors are driving constraints in determining acceptable spacecraft layouts, thermal control subsystems, etc. Also, the production of flight-qualified power processors that have satisfactory performance levels represents a substantial portion of the project cost for a total thrust subsystem. It is clear, therefore, that the power processor is a critical element in the electric propulsion technology, and hence its development status directly impacts on the flight readiness of electric propulsion in general. During this study, a power processor unit for powering and controlling the 30-cm Mercury Electron-Bombardment Ion Thruster was designed, fabricated, and tested. The unit uses a unique and highly efficient transistor bridge inverter power stage in its implementation. The system operates from a 200 to 400 V dc input power bus, provides 12 independently controllable and closely regulated dc power outputs, and has an overall power conditioning capacity of 3.5 kW. Protective circuitry was incorporated as an integral part of the design to assure failure-free operation during transient and steady-state load faults. The implemented unit demonstrated an electrical efficiency between 91.5 and 91.9 at its nominal rated load over the 200 to 400 V dc input bus range. The electrical component weight, including all internal harness, was 15.6 kg including redundant power supplies added to increase reliability. The power processor had undergone a variety of performance and environmental tests, including integration test with a 30-cm ion thruster in both ambient and thermal vacuum environments.</p>			
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FOREWORD

The work described herein was performed principally by personnel within two divisions of the Hughes Aircraft Company. Responsibility for the program resided in the Research Laboratories Division and included program management, system engineering, and digital interface and control circuit design. Power circuit design, packaging, fabrication, and unit integration/test were conducted in the Technology Division of the Space and Communications Group. The work was funded under contract NAS 3-17223 and monitored by Mr. James S. Sovey of the National Aeronautics and Space Administration, Lewis Research Center. The key technical contributors were:

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INTRODUCTION

The weight, efficiency, reliability, and cost of the power processing unit needed to power and control an ion thruster is recognized as a major contributor to the characterization of the total thrust subsystem. The power processor performance factors strongly influence the results of Solar Electric Propulsion (SEP) mission analysis; and, in many cases, these factors are driving constraints in determining acceptable spacecraft layouts, thermal control subsystem, etc. Likewise, the production of flight-qualified power processors which have satisfactory performance levels represents a substantial portion of the projected cost for a total thrust subsystem. The power processor, therefore, is a critical element in the electric propulsion technology, and its development status directly impacts the flight readiness of electric propulsion in general.

The 30-cm Hg electron-bombardment ion thruster developed by Hughes Research Laboratories under contract to NASA-LeRC has reached engineering model status and is generally accepted as the prime propulsion thruster module to be used on the earliest SEP missions. This report describes the results of a related program conducted by Hughes (under contract to NASA-LeRC) to develop a transistorized thermal vacuum breadboard (TVBB) power processor unit (PPU) for this thruster.

The detailed design of the 30-cm thruster TVBB PPU is uniquely different from earlier prime propulsion power processors developed by Hughes, but it relies strongly on the sound technological base and design philosophy established and proven during the development of flight-prototype 20-cm thruster power conditioners under sponsorship of the Jet Propulsion Laboratory.¹ Additional valuable experience to support the TVBB design was gained through a company funded effort to develop high-performance flight type 30-cm-thruster power-processor transistorized bridge inverter circuitry for operation from a 250 V dc bus, and the subsequent incorporation of this circuitry in test consoles for long term ground based thruster testing². One of these consoles,

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during a 10,000-hr endurance test of a 30-cm ion thruster, accumulated more than 11,000 operating hours without an inverter transistor failure-- even though it experienced high-voltage arcing conditions which were far more severe than would be expected under normal operating conditions.³

At the program's inception we recognized as potentially the most difficult problem the safe, low component-stress operation of the proposed transistorized power conditioning circuitry from a contract-specified 200-400 V dc input power bus. As the program progressed, various problems did occur because of the relatively high bus voltage specification. The availability of applicable switching transistors was limited, particularly high-power devices for use in high-frequency, high-performance circuitry. Ultimately this led to the necessity for devising several innovative schemes for drive modulation and protective stress control to provide the desired transistor voltage and current margins. Side benefits resulting from this effort included simplified power-inverter drive circuitry, extremely low dissipation in the power transistors, and improved system efficiency.

The power processor which resulted from the development program is believed to represent a significant technological advancement for such equipment, when judged on the basis of specific weight, electrical efficiency, projected reliability, and total power conditioning capability. Furthermore, while the design was guided by the requirements of the 30-cm mercury ion thruster and a solar electric propulsion mission, the specific power conversion techniques which were evolved should be of general interest to the power electronics community.

The following sections of this report describe the hardware implementation and the system performance achieved, and summarize testing at Hughes and NASA-LeRC.

ELECTRICAL DESIGN DESCRIPTION

In this section, we will discuss the electrical requirements imposed on the power processor by the thruster and how the supplies in the power processor are configured to meet these requirements, and will give a basic description of the individual supplies. "

Requirements

The 30-cm ion thruster requires 12 power supplies to achieve and maintain steady-state operation. Specifications for the individual supplies are listed in Table 1. This table shows, for each supply, a maximum and a nominal design rating. Although the differences between these ratings may seem excessive, they are required, either to adequately cover the thruster-to-thruster manufacturing variations, or to maintain steady-state thruster operation when a perturbation (i.e. an arc) occurs. Two of the supplies listed, the cathode and neutralizer heater supplies, are used only during startup of the thruster. Once steady-state operation is reached, enough heat is generated in the region of the cathodes to allow these supplies to be turned off. Also, the isolator heater supplies are generally turned off after startup. All of the supplies listed in Table 1 have filtered dc outputs which are closed-loop regulated on either output current or voltage, and programmable over their full output range via 0 to 5 volt dc input control signals. They are designed to withstand output shorts or shorts between any combination of supplies. As indicated in Table 1, the outputs of the supplies are referenced relative to four isolated system reference potentials. This isolation has been achieved in most instances without significant penalty through the natural necessity of incorporating load-matching transformers.

The maximum continuous output capability of the power processor is 3475 W when all supplies are operating simultaneously. During normal operation of a 30-cm ion thruster at a 2 A beam level, the output power required is typically 2750 W. The 724 W of additional

Table 1. 30-cm Thruster Power Supply Specifications

Supply No.	Supply Reference Point	Supply	Max Power, Watts	Design Rating Voltage and Current: V, A		Regulation, Type and $\pm\%$	Ripple, $\pm\%$, p-p
				Maximum	Nominal		
1	Ground	Main vaporizer	20	10V at 2A	7V at 1A	I, $\pm 5\%$	$\pm 2\%$
2	Ground	Cathode vaporizer	20	10 at 2	3.5 at 1	I, 5	2
3	Screen	Cathode heater ¹	90	15 at 6	9 at 4.5	I, 5	2
4	Screen	Main isolator and cathode isolator ¹	40 ⁴	10 at 2	4.5 at 1	I, 5	2
5	Neut. Rtn	Neutralizer heater ¹	50	10 at 5	8.5 at 4.2	I, 5	2
6	Ground	Neutralizer vaporizer	20	10 at 2	3.5 at 1	I, 5	2
7	Neut. Rtn	Neutralizer keeper ²	60	20 at 3	12 at 2	I, 5	2
8	Screen	Cathode keeper ²	60	60 at 1	10 at 0.5	I, 5	2
9	Screen	Discharge ³	585	45 at 13	37 at 13	I, 1	2
10	PPU Common	Accelerator	100	1000 at 0.1	500 at 0.008	V, 2	3
11	PPU Common	Screen	2420	1100 at 2.2	1100 at 2	V, 1	1
12	Screen	Magnetic baffle	10	2 at 5	2 at 4	I, 5	5

¹On during startup only.

²H V Section: 1 kV with 20-mA short-circuit capability.

³Open-circuit voltage: ≥ 60 V.

⁴Dual Supply.

power capability built into the unit is provided to satisfy sequential peak power requirements of certain supplies during thruster startup that are cut back or turned off after a steady-state run condition is achieved.

Various supply outputs are required to be displayed as telemetry. The list of telemetry signals is given in Table 2. These signals are selected by and displayed on the digital display panel.

Functional Block Diagram

The manner in which the TVBB power processor is configured is indicated in Figure 1. The high-powered screen and discharge supplies operate directly from the 200 to 400 V dc input power bus. The remainder of the supplies, which are considerably lower in power, derive their input voltage past the line regulator at a level of 180 V dc, $\pm 1\%$.

Table 2. Telemetry
(Prior to A/D Conversion; 0-5 V range)

Supply		Current (A)	Voltage (V)
1	Main vaporizer	0-2	
2	Cathode vaporizer	0-2	
3	Cathode heater	0-10	
4a	Main isolator	0-2	
4b	Cathode isolator	0-2	
5	Neutralizer heater	0-10	
6	Neutralizer vaporizer	0-2	
7	Neutralizer keeper	0-4	0-30 ⁽²⁾ (0-3V) 30-1030 (3-5V)
8	Cathode keeper	0-1	0-30 ⁽²⁾ (0-3V) 30-1030 (3-5V)
9	Discharge	0-20 ⁽¹⁾	0-50
10	Accelerator	0-0.05	0-1000
11	Screen	0-2.5	0-1500
12	Recycle counter		0-5V
(1) Measures emission current.			
(2) See Table 1.			

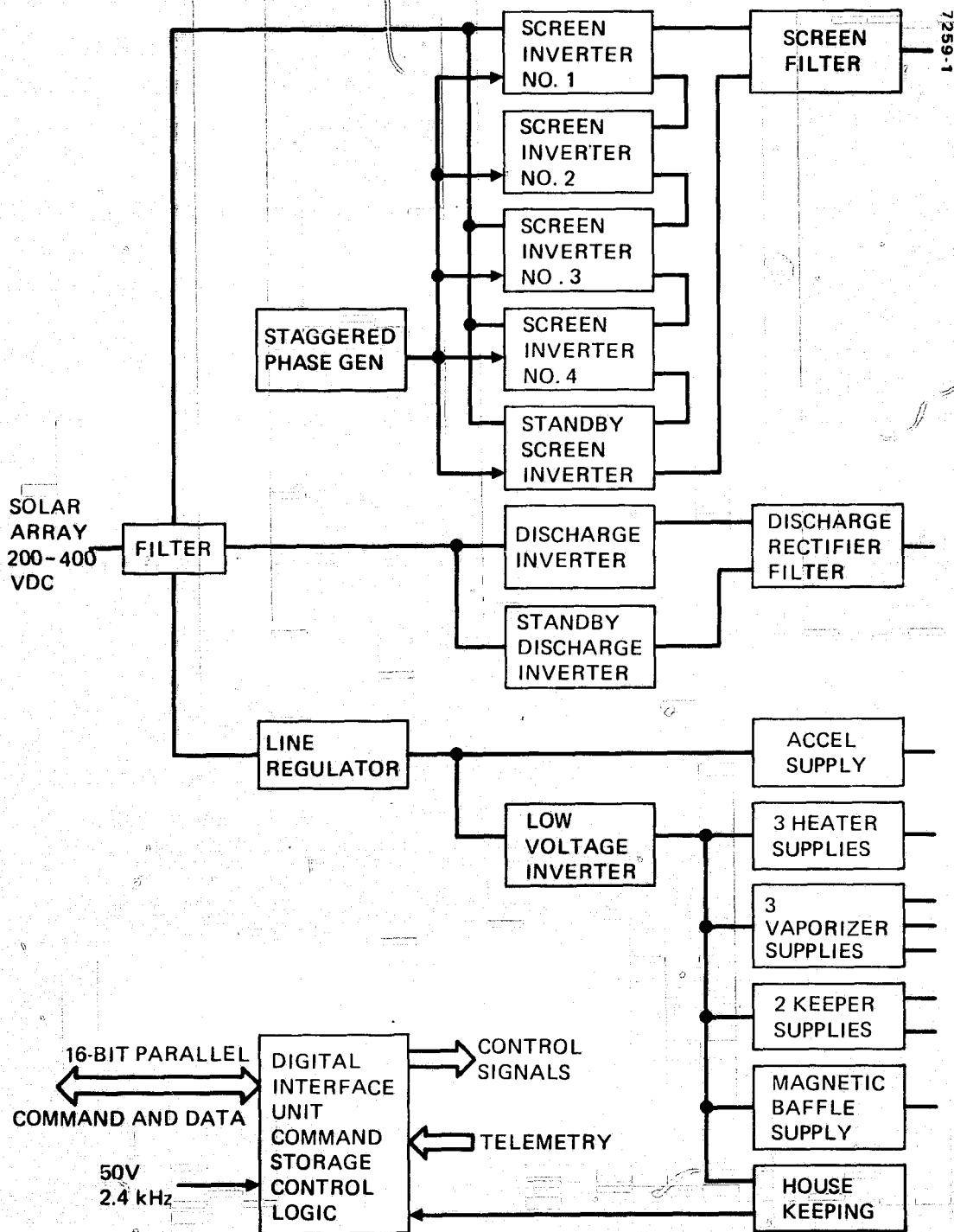


Figure 1. 30 cm thruster thermal-vacuum breadboard power processor functional block diagram.

The screen supply is the highest-powered supply in the power processing unit. It is capable of conditioning and regulating up to 2420 W of output power. The output voltage is programmable over the range of 0 to 1100 V via a 0 to 5 V dc control signal from the Digital Interface Unit (DIU). The supply's upper continuous-current rating is 2 A, although long-term operation at its maximum rating of 2.2 A has been demonstrated. Circuitry to detect and safely control component stresses due to continuous or transient load faults has been incorporated as part of the supply.

Five transistorized bridge inverters are used to implement this supply. The 275 V dc outputs of these inverters are in series to produce the required screen output of 1100 V. During operation, four of the inverters are driven by staggered phased 10-kHz logic signals from the control circuitry. A fifth, redundant inverter is included which automatically comes on-line in the proper driven phase to replace a failed prime inverter, and increase the supply's reliability through partial redundancy.

Because of the staggered-phased 10-kHz operation, the fundamental ripple frequency seen by the input line filter and screen output filter is 80 kHz. This high ripple frequency has made it possible to meet system ripple specifications at significantly lower weights than could be achieved with single-phased 10-kHz operation. An added advantage is that the resonant frequency of the output filter for the four-phase system is higher, making it possible to achieve a faster regulator response.

The discharge supply employs the same basic bridge inverter as used in the screen supply. Constant current regulation of the output is achieved by pulsewidth modulation of the power stage as a result of comparing the sensed output-current level with a command reference setpoint stored in the DIU. A standby redundant inverter is included in the TVBB implementation. The redundancy is carried through the power stage to the output rectifiers. There is, however, a single filter inductor and set of filter capacitors. The digital drive signals

from its controlling pulsewidth modulator are automatically directed from the main inverter to the standby in case of a failure.

All input bus power is routed through a single-stage L-C input filter sized to limit line ripple current to 1% when the system is operated at rated power.

The lower-powered heater, vaporizer, keeper and magnetic-baffle supplies are all designed around a standardized magnetic-amplifier-controlled supply configuration. Primary input to these supplies is 180 V 10-kHz square-wave power from the low-voltage ac distribution inverter. In each supply, the magnetic-amplifier-controlled pulsewidth-modulated primary waveform is applied to an output transformer designed to provide the necessary impedance matching and voltage isolation. The secondary output is then rectified and L-C filtered.

The negative high-voltage accelerator is implemented using a duty-cycle-modulated energy-storage boost converter operating from the pre-regulated 180-V dc bus. This supply approach is well adapted to safely handle screen-to-accelerator high-voltage overloads.

Each of the above supplies is programmable over its full output range via a 0- to 5-V dc control signal and in turn provides a 0 to 5 V dc analog telemetry signal. These two types of signals constitute the electrical interface between the command, control, and data-handling portions of the power processor in the DIU and the 12 basic power supplies.

Communication between the power processor and external command and data equipment follows a strobed 16-bit parallel-digital word format. Externally generated commands which direct basic operation of the power processor are stored in the DIU. These are acted on by internal logic and control circuitry to achieve the desired automatic sequential and closed-loop control associated with the various system states ranging from the initial thruster start-up to unattended steady-state operation.

Basic Power Inverter

The power processor which has resulted from the development program utilizes a standardized or basic power inverter to implement both the screen and discharge supplies. The development and optimization of this transistorized inverter and the associated drive modulation scheme consumed a significant portion of the total program effort. Since the screen and discharge supplies condition approximately 98% of the total input thruster power (at 2 A beam), the efficiency of these inverters has the predominate impact on the overall power processor performance. The two supplies are also subject to load-initiated transient overloads which makes it mandatory that the power transistors be operated under known and controlled stress conditions to assure long-term system reliability.

The remainder of this section will describe the basic inverter configuration developed, its modes of operation, and certain advantages it has relative to more conventional approaches.

Figure 2 is a simplification of the basic bridge inverter configuration. The two switches on each side of the inverter are alternately turned on and off by a square-wave drive signal, and the phase of the drive relative to each side can be controlled independently. In this mode of operation, the pulsewidth of the output is controlled by sliding the phase of the B side of the inverter from 0° to 180° with respect to the A side of the inverter. If the two sides of the bridge are switching up and down, in exact phase, no output voltage will be applied across the power transformer. As the two sides of the bridge slide out of phase, pulses of voltage are applied to the power transformer during the interval which represents the phase difference between the two halves of the bridge. If the two halves of the bridge are 180° out of phase, a full square-wave of voltage is applied across the power transformer.

There are significant advantages to driving an inverter with two square-waves that are slid in phase with one another to produce a duty-cycled modulated output. If a pulse-driven bridge inverter is

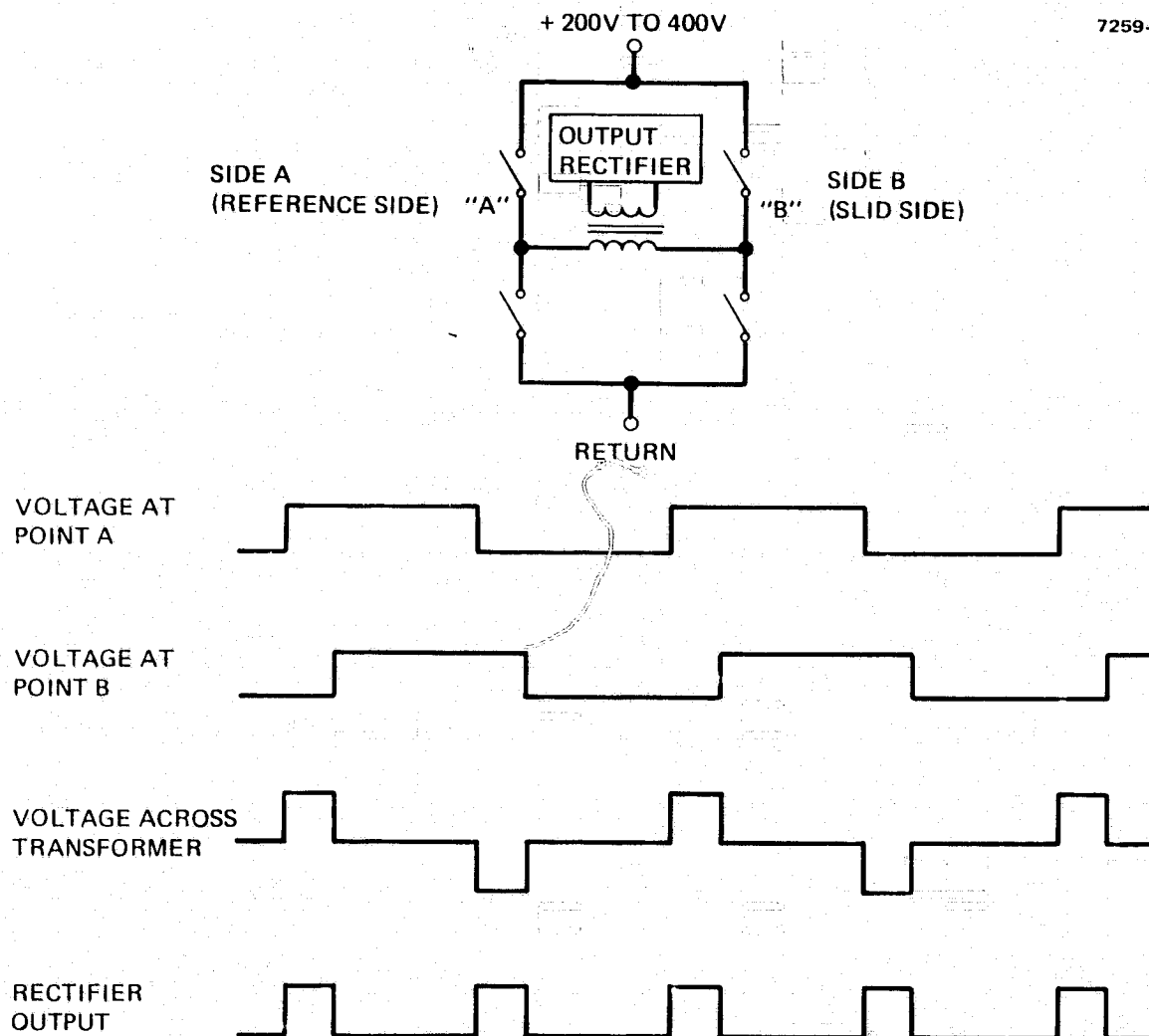


Figure 2. Simplified basic bridge inverter.

used, two opposite transistors would be driven on simultaneously, and then the bridge turned off completely; the other transistors would be driven on simultaneously, then the bridge driven off completely. A significant amount of gating logic must be used to form these pulses.

A second, and perhaps more important, reason for operating the bridge in this manner is the fact that the output voltage from the bridge looks exactly as predicted. That is, the reactive currents in the bridge or the load do not cause the bridge to put out unexpected voltages. It is these unexpected voltages due to reactive currents which cause the normal pulse-drive bridge to be extremely difficult to control at low output voltages. The pulse-drive bridge has a serious tendency to peak its output voltage under light loads and low commanded outputs.

The basic inverter is shown schematically in Figure 3A. It is basically made up of the four power transistors Q1 through Q4, an output power transformer T5 and reactive diodes CR5 through CR12. Each side of the inverter is driven with a notched square-wave which is formed by applying a low-power Q, \bar{Q} square-wave input to individual driver and one-shot circuitry for the reference and slid side. The reference driver and one-shot drive transformers are T2 and T1; while the slid-side driver and one-shot drive transformers are T3 and T4.

Referring to the reference side, the two windings of driver transformer T2 are connected in opposite phase to the base emitters through current-limiting resistors R1 and R3. The two windings of one-shot transformer T1 are connected in phase to the base emitters through current-limiting resistors R2 and R4, and through diodes CR1 through CR4. Voltage is applied to transformer T1 just before the square-wave output of transformer T2 toggles (changes polarity).

Assume transistor Q1 has been on, and transistor Q2 has been off. When voltage is applied to T1, reverse base current will flow out Q1 into T2; also, the current flowing out of T2 will be diverted from the base of Q1 into T2. Transformer T2 toggles while T1 is on. When it toggles, current will flow from T2 through R3 into T1. Voltage

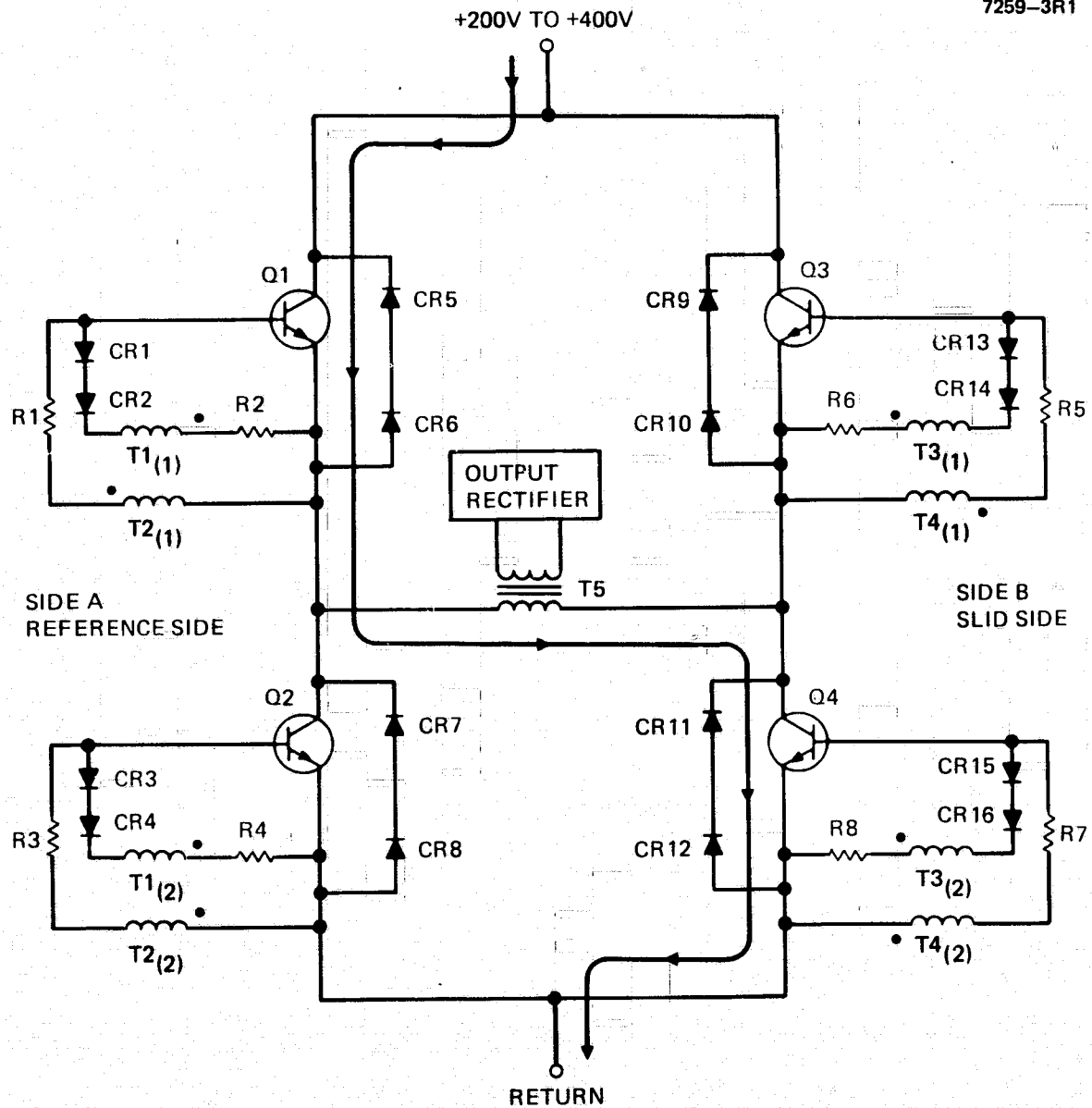


Figure 3A. Bridge inverter current paths during half-cycle operation (Q1, Q4 on).

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is applied to T1 for approximately 5 microseconds; after that time current is allowed to flow into the base of Q2, turning it on.

At the end of the half-cycle, voltage is again applied to T2; T1 is toggled, and the circuit reverts to the Q2 off, Q1 on condition. The slid side base drive circuitry operates in a manner identical to that of the reference side.

Figures 3A through 3E indicate the paths traversed by the currents in the bridge during a half-cycle of operation. Assume Q1 and Q4 are on, causing current to flow in the direction of the arrow shown in Figure 3A. Next, Q4 will be turned off. When the storage time of Q4 has elapsed, current will flow in the direction of the arrow shown in Figure 3B. When the five-microsecond voltage across T3 has elapsed, Q3 will be turned on and it will operate in the inverted mode conducting some of the current as shown in Figure 3C. The current flowing in this path will be a combination of commutating T4 primary current and commutating load current.

Next, Q1 will be turned off, and, after its storage time, T5 magnetizing current will flow as shown in the arrow of Figure 3D. Since the full input line voltage will be across the transformer during this interval, the current will go quickly to zero. Next, base drive will be applied to Q2, and current will flow in the direction of the arrow shown in Figure 3E. In the next half cycle, the bridge will operate in a similar manner.

Note that only one transistor switches at a time; that Q3 switches on when there is very little collector-emitter voltage, and that Q1 switches off with little or no collector current. That is, the significant losses in the reference side transistor are only switch-on losses; and the significant losses in the slid side are only switch-off losses. The bridge inverter described here has, therefore, only half the losses of a standard pulsed-driven bridge inverter.

+200V TO +400V

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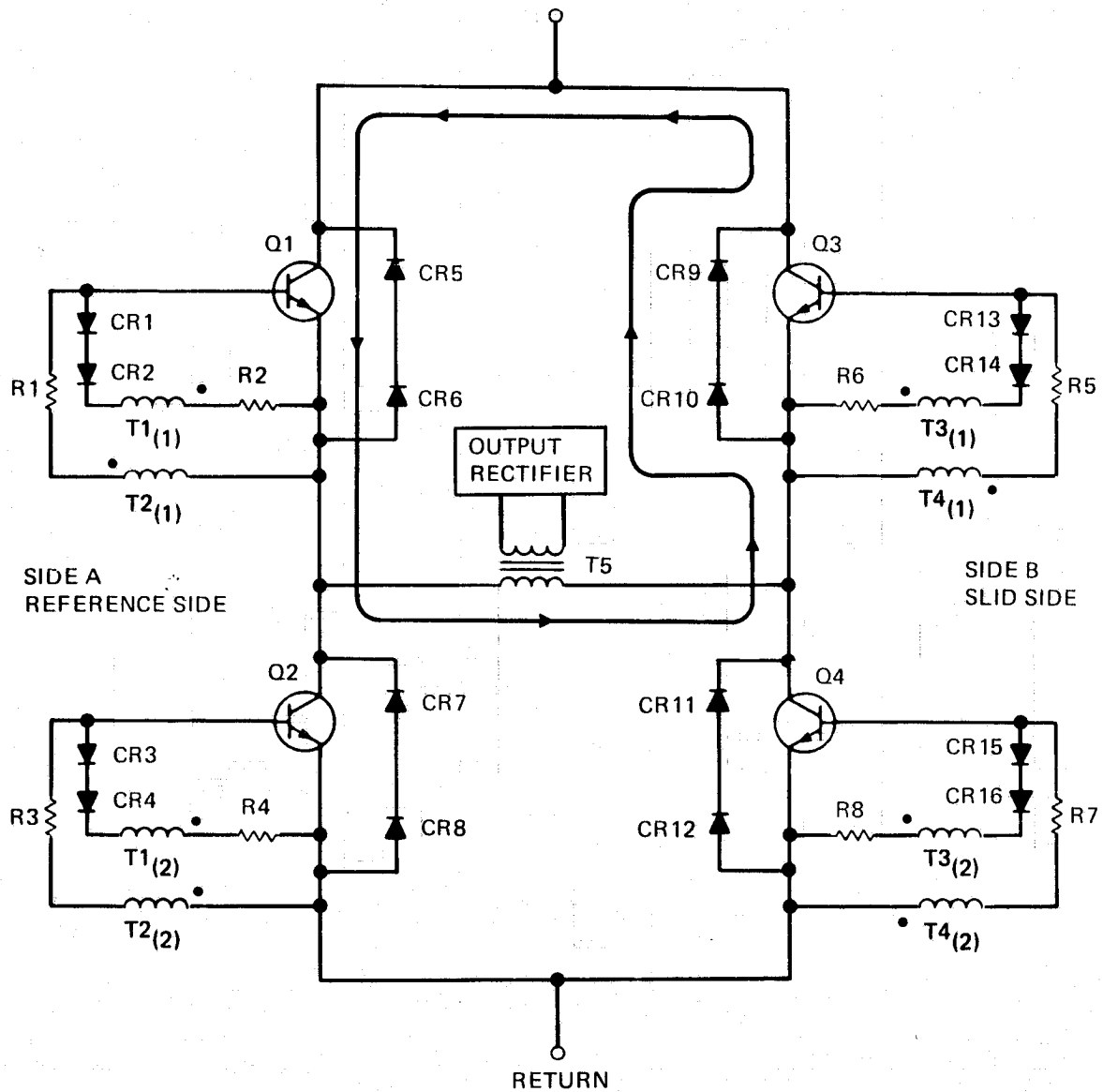


Figure 3B. Bridge inverter (Q1 on, Q4 off).

+200V TO +400V

7259-5R1

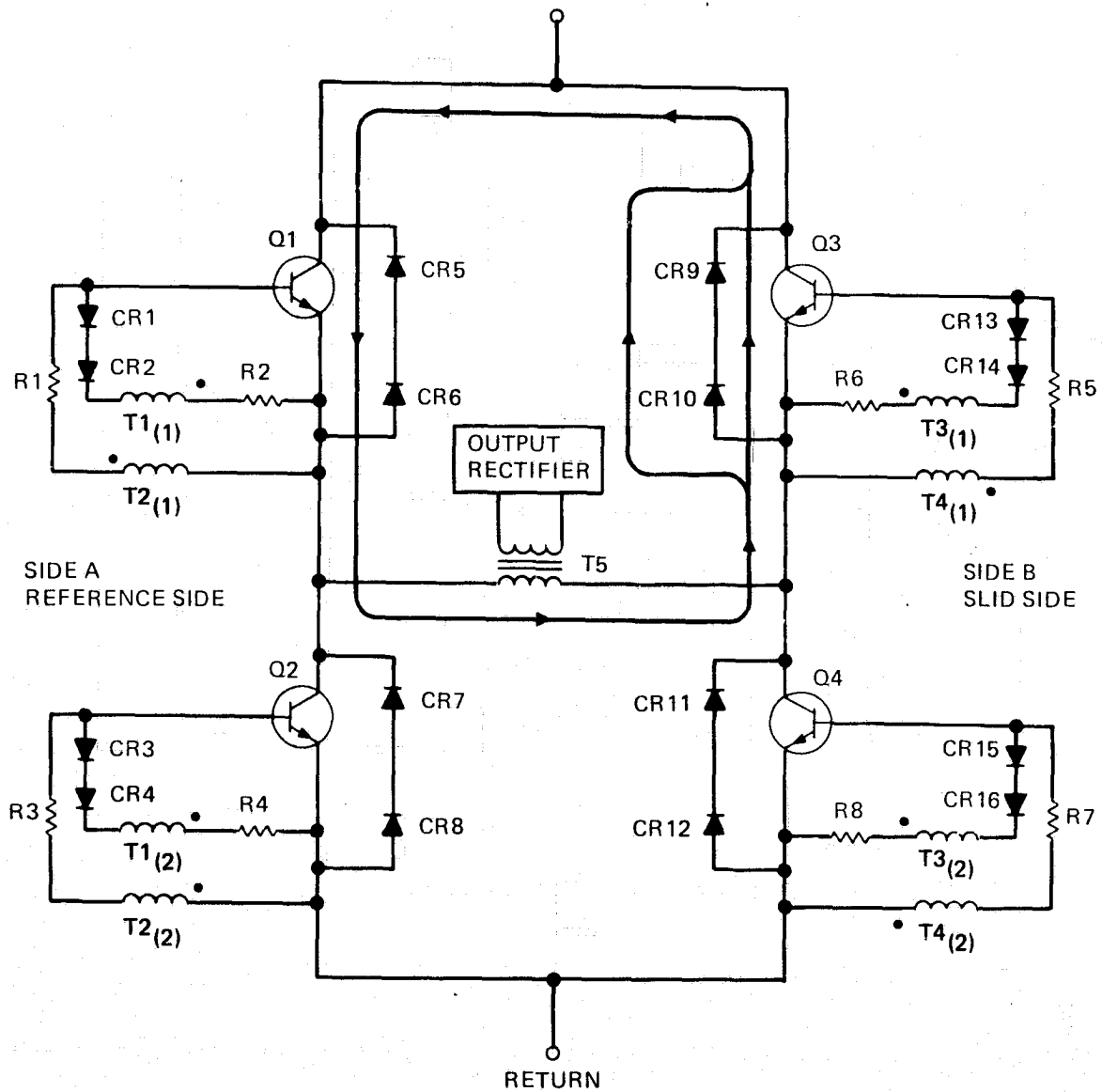


Figure 3C. Bridge inverter (Q1, Q3 on).

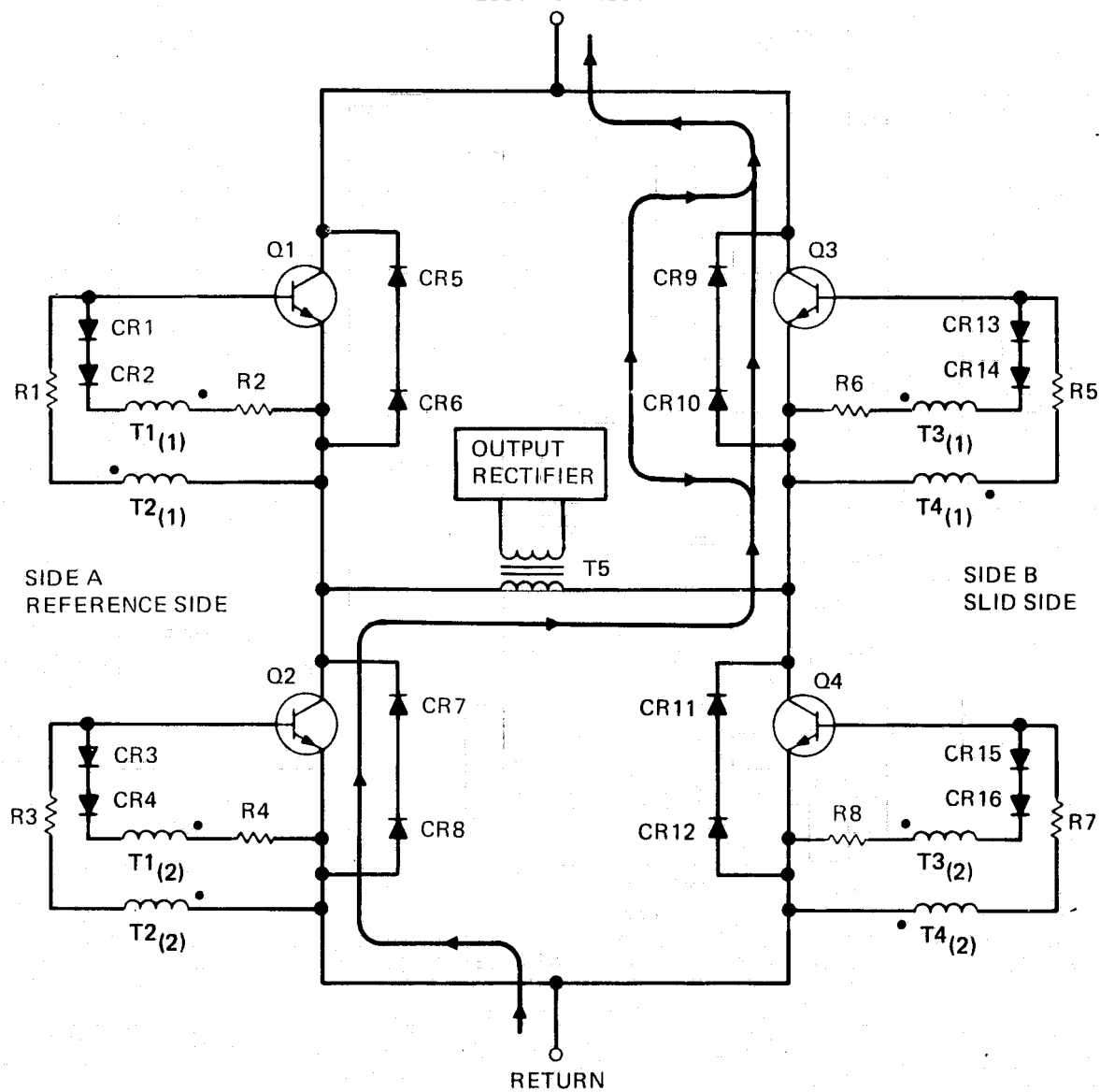


Figure 3D. Bridge inverter (Q1 off, Q3 on).

+200 TO +400V

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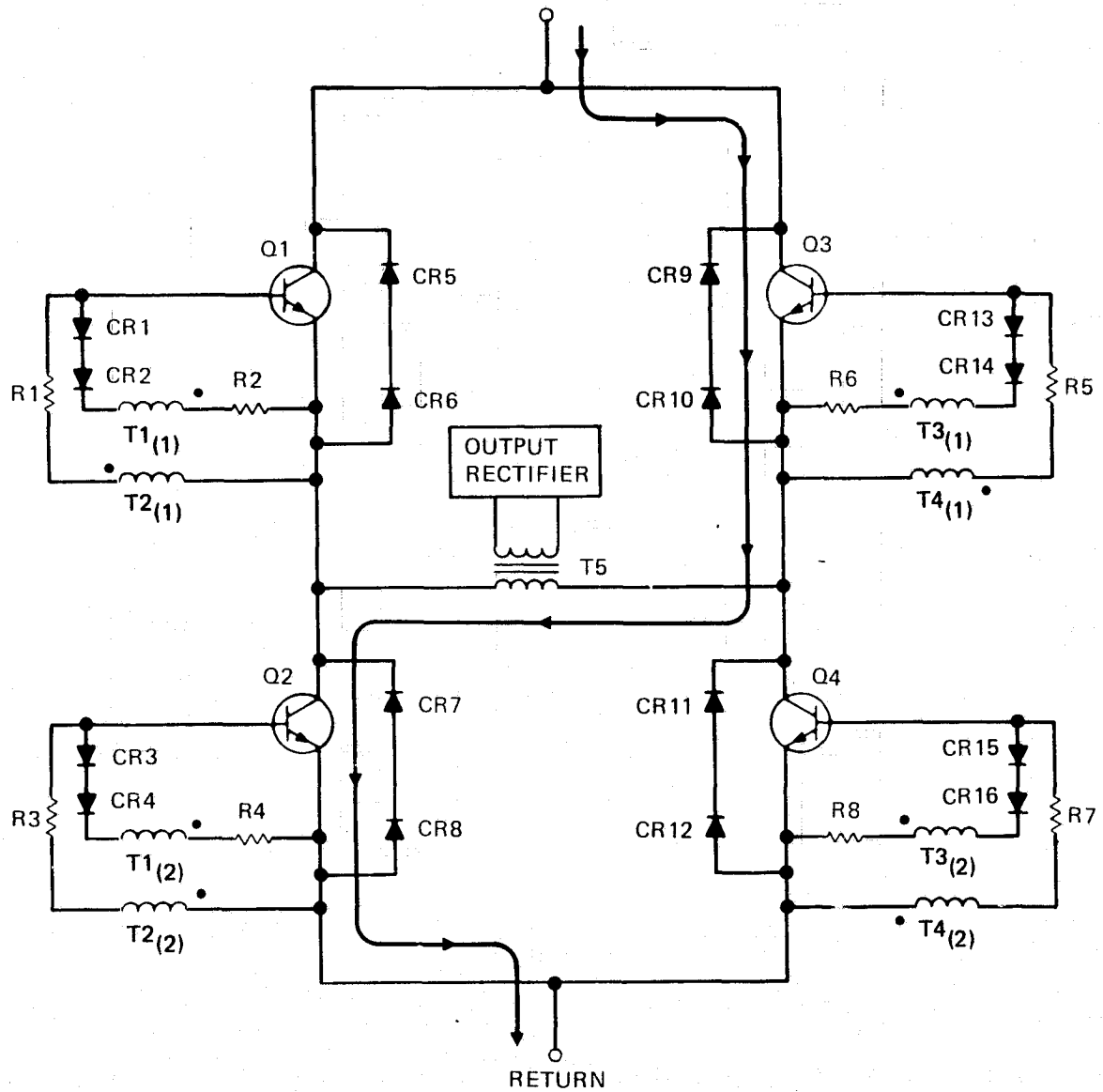


Figure 3E. Bridge inverter (Q2, Q3 on).

Screen Supply

The screen supply is the largest single supply in the TVBB power processor. This supply regulates and conditions approximately 2.4 kilowatts of power derived from the 200 to 400 volt solar array bus. The supply output is commandable up to 1100 volts at 2.2 amps maximum, with a nominal running condition of 1100 volts at 2 amps. A four-phase bridge inverter configuration was selected for the implementation of this supply to minimize the weight of the input and output filters. The supply actually uses five basic inverter power stages (previously described) connected in series as shown in the screen system block diagram (Figure 4). The fifth inverter stage is a standby redundant inverter, and, should any one of the four normally running inverters fail, it is driven in the phase position of the failed stage. Having four inverters operating in a staggered phase condition at a basic frequency of 10 kHz produces ripple currents with a fundamental frequency of 80 kHz. This high ripple frequency allows lightweight designs of the input and output filters, with the added advantage of making possible faster regulator response due to the higher resonant frequency of the output filter.

The drive for the inverter power stages is produced by the digital modulator portion of the staggered phase generator. This circuitry receives the 0 to 5 volt control signal and an on/off command from the DIU. The screen output voltage is compared to the control signal, and the drive to the inverter stages is adjusted to achieve regulation of the supply. The staggered-phase generator also contains the current-limiting circuitry that shuts down the supply when there is a current overload, as well as the circuitry that senses a failed power stage.

Discharge Supply

The discharge supply⁴ is the high-current low-voltage supply which maintains the arc or discharge within the thruster ionization chamber.

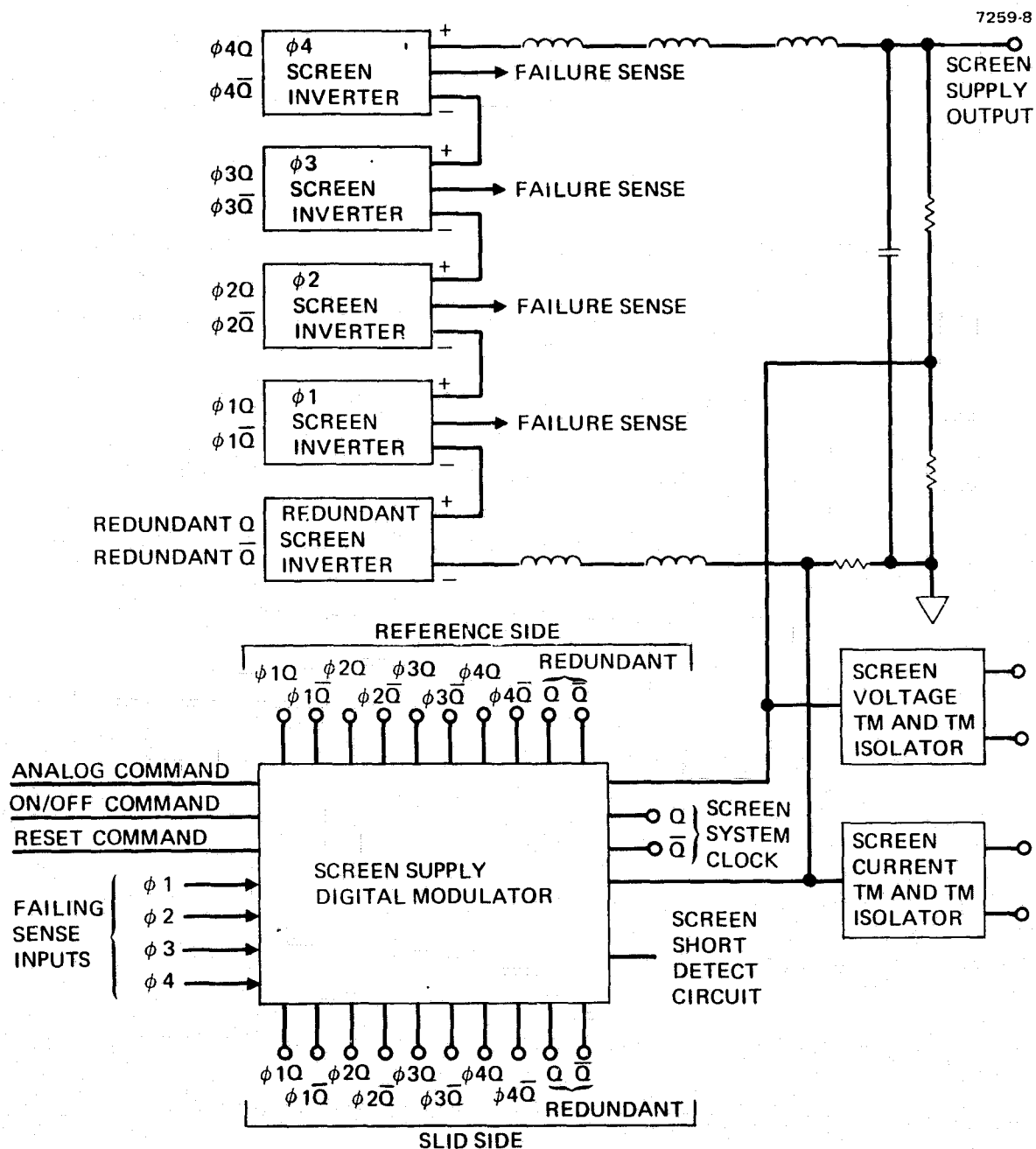


Figure 4. Screen system block diagram.

The output of this power supply is programmable and current-regulated. This supply provides approximately 45 volts at an output current up to 13 amps.

The open-circuit voltage of this supply must be sufficiently high to initiate a discharge within the thruster. A minimum open-circuit voltage of 60 volts is required. The supply must also be capable of dynamically maintaining an arc, once the arc is initiated, and must maintain this arc while actively preventing any electrical components from being overstressed.

The negative output of the discharge supply is connected to the positive output of the screen supply. Therefore, the discharge supply output is referenced at approximately 1100 volts above the PPU common. Both current feedback and current telemetry are obtained from a single magnetic amplifier that provides the necessary high-voltage isolation. High-accuracy voltage telemetry is obtained from a magnetically isolated voltage transducer. This voltage transducer also provides a small amount of current which, under the no-load condition, charges the output capacitor of the arc supply to the point where arc ignition can occur.

During normal operation, the power inverter discharge supply functions identically to the screen inverter described previously. The output transformer of the discharge inverter is constructed in a similar manner to that of the screen inverter, with the exception that the turns ratio is changed to reflect the low output voltage. A full-wave, center-tap rectifier is used on the output of the discharge supply rather than a bridge, as used in the screen supply. The center-tap rectifier offers a lower forward voltage drop than the bridge, and is therefore more efficient. The discharge supply output filter is comprised of a 0.8 mh inductor and three 60 μ f capacitors in parallel.

A standby redundant discharge inverter is provided. The redundancy is carried through the power stage and to the power rectifiers. There is, however, a single filter inductor, a single feedback control mag amp, and a single output voltage sensor. The digital signal from the pulse-width modulator is automatically directed from the main inverter to the standby inverter in case of a failure.

The function of the discharge modulator is to supply two phases of 10 kHz signal to the discharge inverter and standby inverter. These inverters are similar to the screen inverters and require the same type of logic signals. The modulator uses a pulse width comparator which is driven with a 20 kHz ramp on its input and each pulse out is steered to drive the bridge in alternative directions. By gating the comparator output with two one-shot multivibrators, the bridge will continue to be clocked correctly under conditions of modulator saturation or cutoff.

Figure 5, the discharge timing diagram, is an illustration of the modulator's dynamic performance from full-off to full-on and then to off again. The 20 kHz clock is made by combining two phases of the 10 kHz screen reference clock through two NOR gates.

AC Distribution Subsystem

The ac distribution subsystem used in the TVBB power processor is comprised of the line regulator, the low voltage inverter, and the magnetic amplifier supplies.

Line Regulator

The line regulator⁵ is a series switching buck type regulator which is capable of conditioning approximately 500 watts of power. A block diagram of the line regulator appears in Figure 6.

This regulator is used to condition the 200 to 400 volt line to produce a regulated 180 volt output. The output of 180 V was selected for two reasons: A buck regulator output is always less than the minimum input line voltage; and the minimum pulse width of the switching power transistor is determined by the difference between the output voltage and the minimum input line voltage. For these reasons, the output of a buck regulator is quite often selected to be 10% less than the minimum input line voltage.

This regulator has a 100% dynamic range control capable of operating from full-off to full-on with a small amount of hysteresis at each

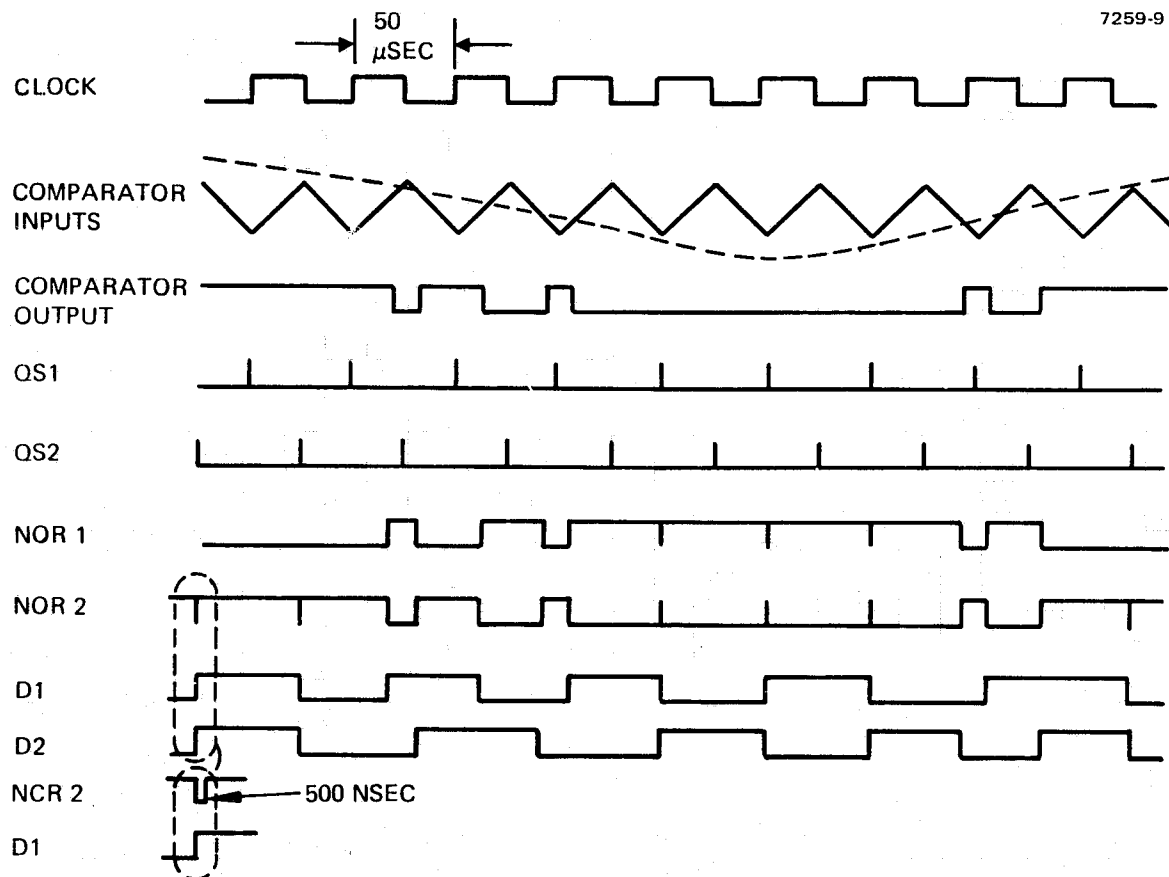


Figure 5. Discharge modulator timing diagram.

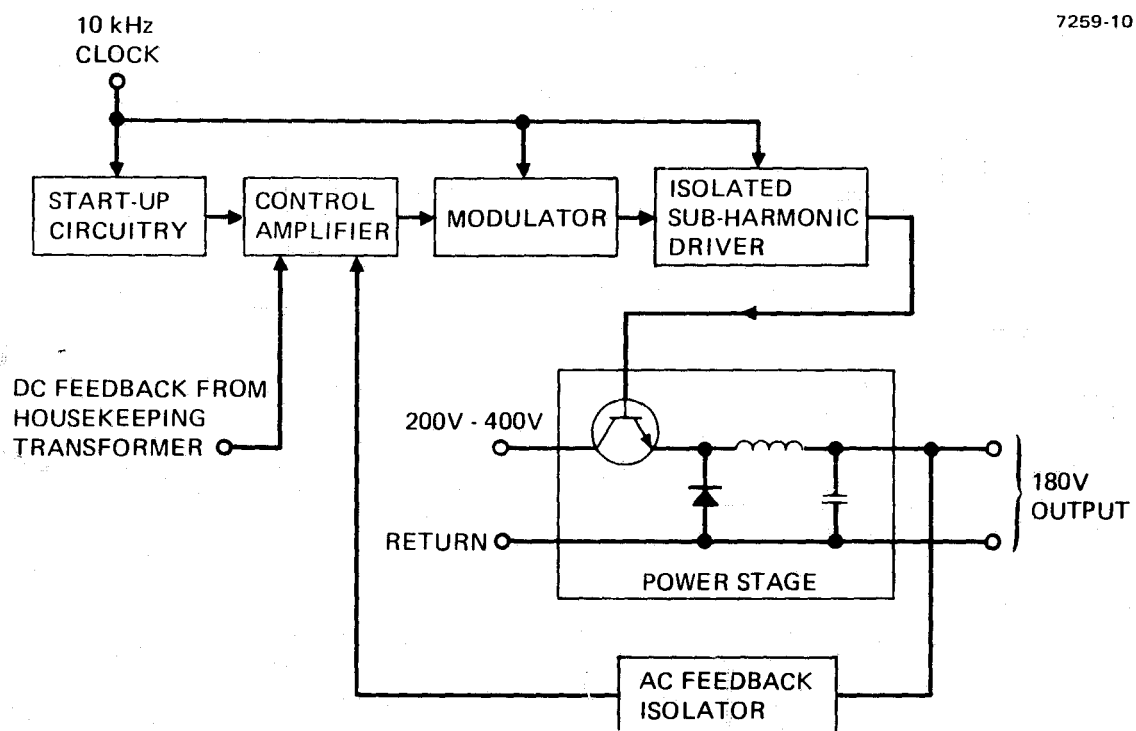


Figure 6. Line regulator block diagram.

end of the control range. This hysteresis is due primarily to the storage time of the power transistor, which sets the minimum pulse width which may be delivered. The line regulator is used to power two specific types of load. The first load is the 10-kHz square-wave inverter, the output of which provides ac power for the magnetic amplifiers which supply power to the heater and keeper loads. The 10-kHz inverter also provides the +15 volt and ± 6 volt housekeeping power. The solar panel ground and the housekeeping ground in this system are at different potentials. Because of this, an isolated form of feedback must be used to maintain 180 volt regulation. The 15 V winding on the housekeeping power transformer is used as the feedback voltage for the line regulator.

The principal sources of dissipation are the power transistor, the inductor, and a few components in the drive circuitry. These dissipative components have been separated to obtain a uniform thermal density on the plate.

Low-voltage Inverter and Magnetic Amplifiers

The low-voltage inverter shown in Figure 7 is a parallel-current-feedback square-wave inverter designed to operate at 10 kHz and condition approximately 400 watts. This inverter is operated from the pre-regulated 180 volt dc bus, which is conditioned by the line regulator, and provides outputs for the +15 Vdc and ± 6 Vdc housekeeping power. The 15-volt winding on the output transformer is used as voltage feedback for the line regulator.

A 72 V ac output is provided to power the nine magnetic-amplifier-controlled supplies and to act as the drive reference for current sensing. The nine supplies are the main vaporizer, cathode vaporizer, cathode heater, main and cathode isolator, neutralizer heater, neutralizer vaporizer, neutralizer keeper, cathode keeper, and the magnetic baffle. Designs for these supplies fall into three basic configurations shown in functional diagram form in Figures 8 through 10.

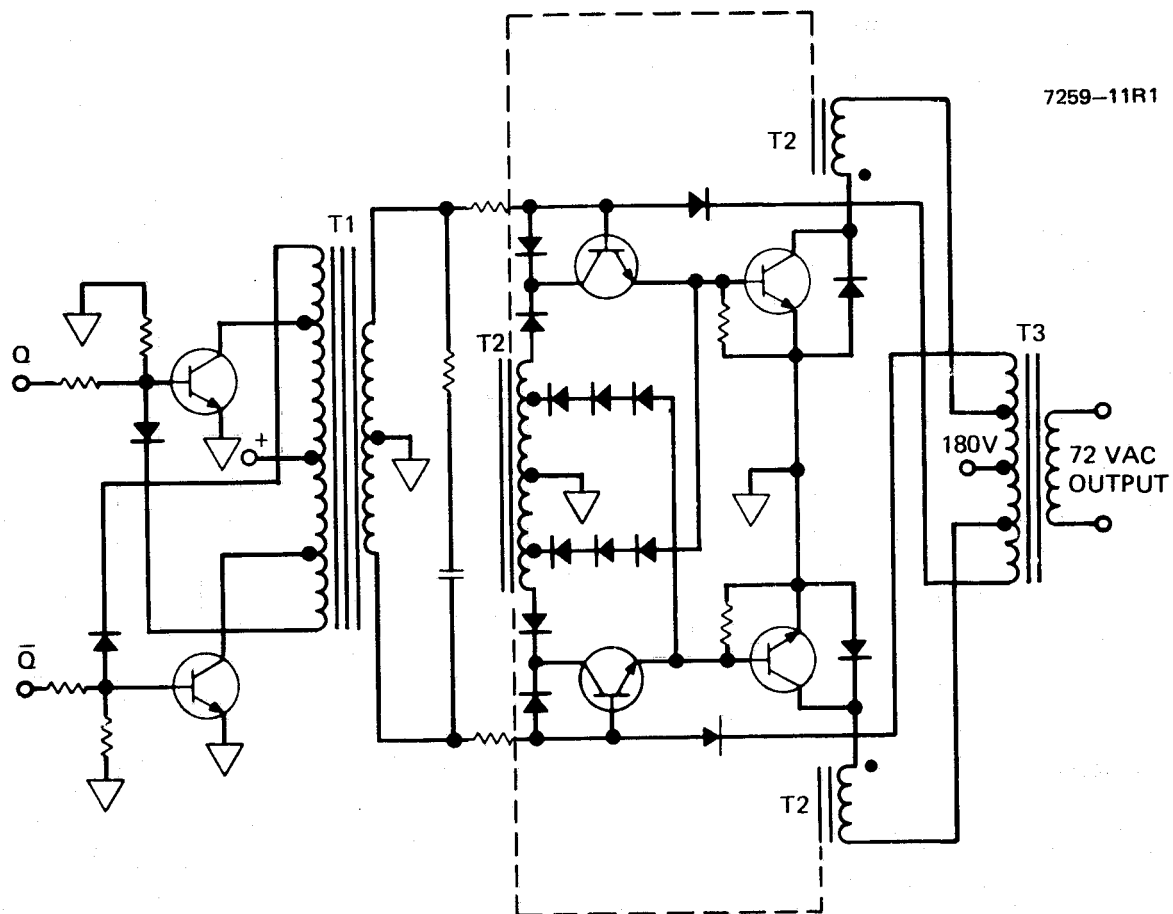


Figure 7. Low-voltage inverter.

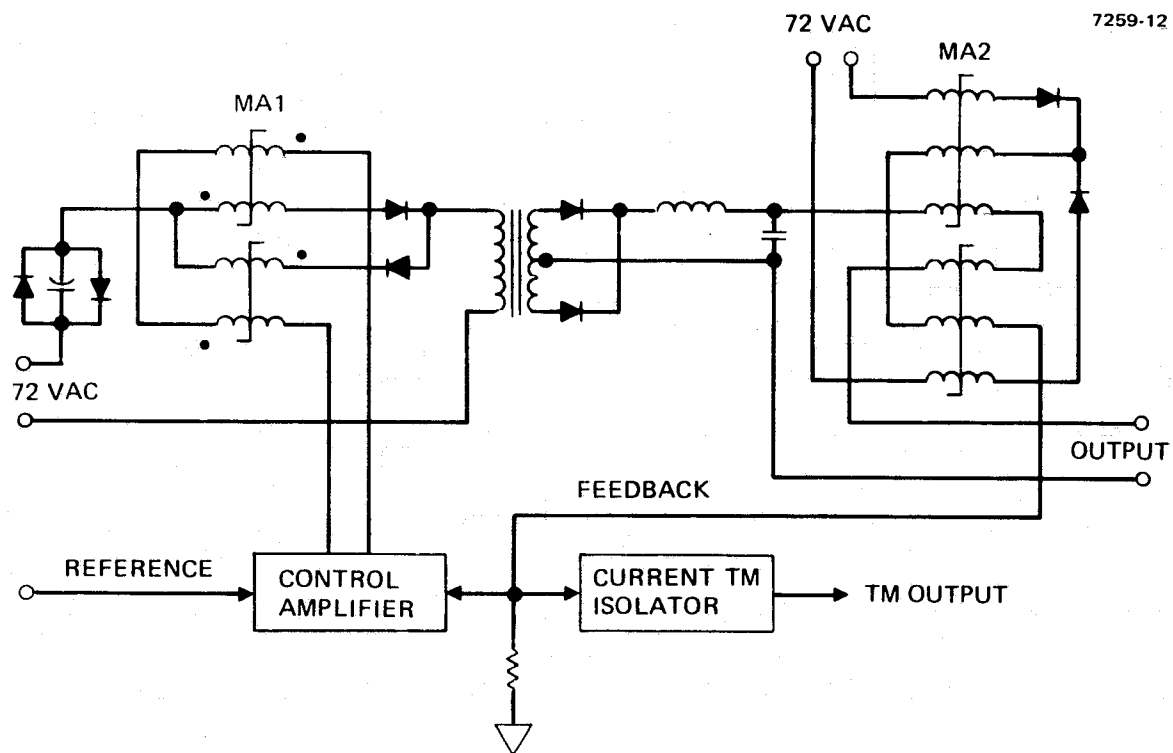


Figure 8. Magnetic amplifier block diagram (applicable to the main, cathode, and neutralizer heater supplies, and the magnetic baffle supplies).

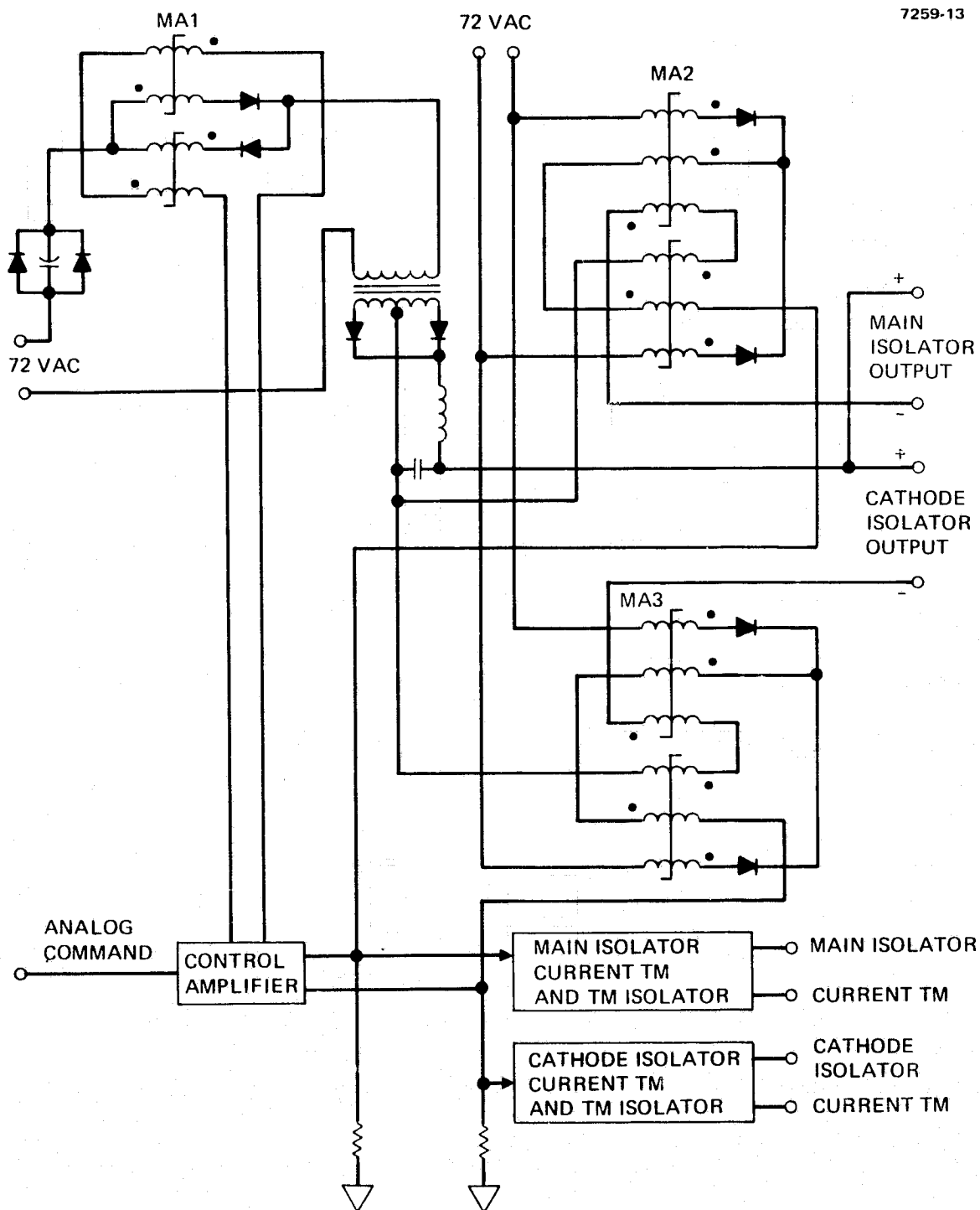


Figure 9. Main and cathode isolator supply functional block diagram.

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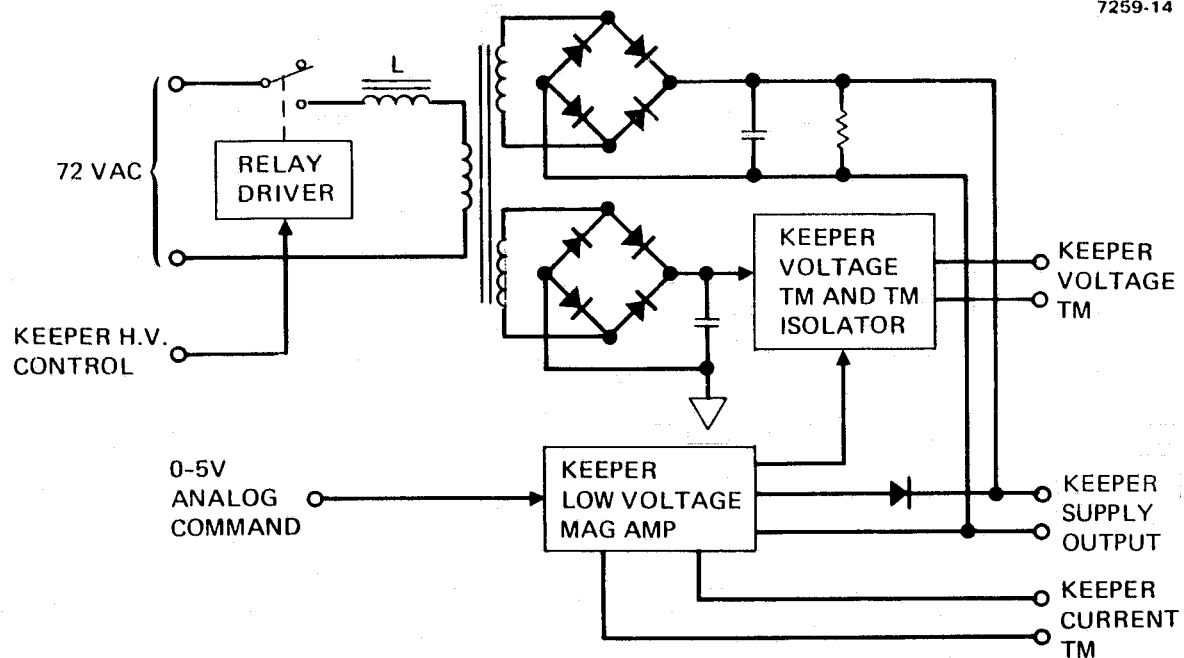


Figure 10. Keeper supply block diagram (applicable to both the cathode and neutralizer keeper supplies).

The neutralizer keeper and cathode keeper must each provide at least 1000 volts open circuit and supply at least 20 milliamps to ignite the discharges. The requirements to sustain the discharges for the two keepers are 20 volts at 3 amps and 60 volts at 1 amp respectively. The high voltages are switched off after the system has started.

The low-voltage inverter, magnetic baffle supply, cathode heater, cathode vaporizer, and main vaporizer supply are located on a single module plate. The other supplies - main and cathode isolator, neutralizer heater, neutralizer vaporizer, neutralizer keeper, and cathode keeper - are located on another module plate.

Accelerator Supply

The accelerator supply produces a controllable negative output voltage which is used in the nominal range of -400 to -1000 volts. The supply is a duty-cycle-modulated energy storage boost converter operating from a pre-regulated 180 volt supply. The nominal output current is approximately 5 ma, but, under fault conditions, this supply must be capable of supplying up to 100 ma. The supply is composed of four basic sections: the control amplifier- modulator, driver/output power stage, and the telemetry and current limit section. This supply is shown in block diagram form in Figure 11.

Digital Controller and Auxiliary Equipment

The purpose of the digital controller that was designed to operate in conjunction with the power electronics developed on this program can be summarized as follows:

- Receive 16-bit parallel strobed command words from either a computer or command simulator
- Isolate the command lines and return from PPU, spacecraft and power grounds
- Store the received commands

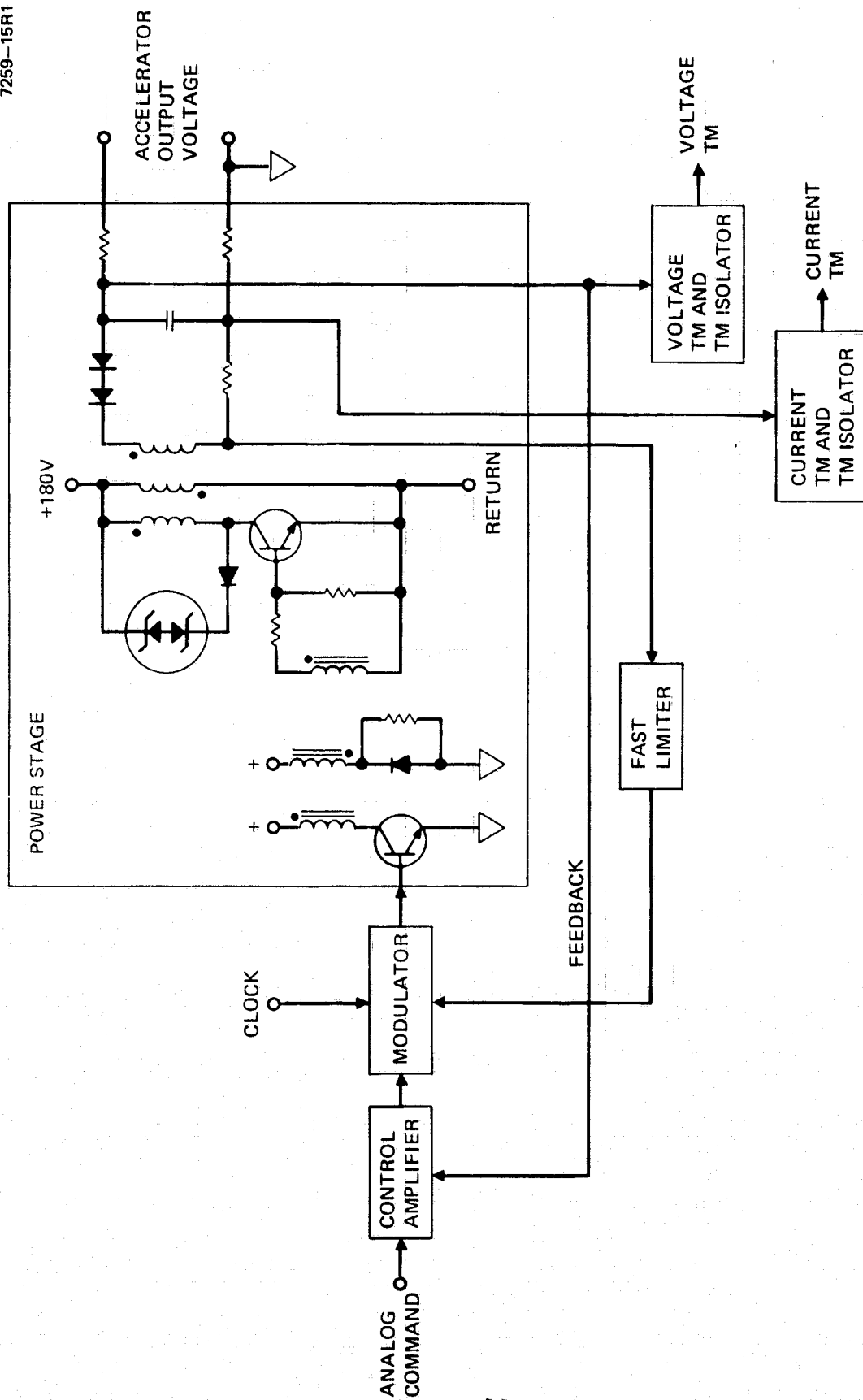


Figure 11. Accelerator supply block diagram.

- Provide setpoints for the various power supplies that are required by the thruster
- Furnish closed-loop proportional control of certain power supplies
- Perform digital to analog (D/A) conversion of specific commands to provide closed loop references and high accuracy setpoints
- Automatically shutdown operation if the input bus voltage falls below 180 volts
- Provide the recycle logic and timing required when a high voltage arc occurs
- Cause a recycle to occur if the input bus current exceeds a value determined by a D/A converted command
- Perform multiplexing and analog-to-digital (A/D) conversion of the 19 channels of analog telemetry

The functions listed above will be discussed in greater detail later in this report.

The design of this controller evolved from the design of the controller developed for the 8-cm diameter ion thruster TVBB power processor (Contract NAS 3-17780). The primary concern in the design of the controller was to keep the parts count to a minimum while preserving independence of functions. Independence of the basic functions was considered important in the design of the controller because it was anticipated that some of the automatic functions and control logic would require change during the program due to new information obtained during the normal course of thruster testing. The functions were kept independent, even though this approach may require additional piece parts, so that any subsequent changes would have the least impact on the program. This is why the controller used parallel paths with a minimum of cross-strapped logic. This reasoning was also applied to the printed circuit card layout. That is, wherever possible, discreet functional blocks of logic were placed on individual cards so that, to modify any one function, only one card would have to be reworked.

To achieve a degree of freedom during thruster operation, a variable setpoint was included for every power supply that did not have a reference generated by a D/A converter. This required that trimpots be included in the design even though this is not considered a "flight" design practice. The trimpots would be replaced with fixed resistors in a flight model.

Because the design of the controller was an extension of previous work, only certain functions were tested prior to the fabrication of the printed circuit cards. Although this approach contained a certain amount of risk, the action seemed warranted based on previous experience in this area. In fact, during integration of the cards, very few design errors were uncovered. These errors were of minor significance and were corrected easily.

The 16 bits that comprise the command word and the strobe pulse that loads the commands into the controller are defined to be standard TTL (not low power) signals. The width of the strobe pulse must be greater than 50 milliseconds. Also, the 16-bit command word must be set prior to the occurrence of the strobe pulse and must remain set for the entire duration of the strobe.

The initial references for the main, cathode, and neutralizer vaporizer, the main/cathode isolator, the cathode and neutralizer heater, and the cathode and neutralizer keeper supplies are from fixed setpoints. Each supply has four setpoints with one of the setpoints being variable.

By selecting certain control options, the operation of the above mentioned supplies can be modified. The main vaporizer supply can go to closed-loop operation and its output will vary in such a fashion as to regulate the beam current at a level determined by a D/A converted reference. The cathode vaporizer will regulate the discharge voltage at a fixed level when in closed-loop control. The neutralizer vaporizer, when in closed-loop control, will regulate the neutralizer keeper voltage as determined by selection of one of four possible setpoints. Either or both of the cathode heater supplies can turn off

once certain thruster operating conditions are established. Also, either or both of the keeper supplies can be cut back during a recycle.

The screen, discharge, and magnetic baffle supplies receive their references from D/A converters, and the accelerator supply receives its reference from a variable setpoint.

Other features of the controller such as recovery from a high voltage arc (a recycle) and detection and correction of low mode thruster operation will be discussed later in this report.

The power required by the controller is initially derived from the 56-Vrms, 2.4-kHz power bus. However, once the TVBB is operating, the power is provided by supplies in the TVBB that operate off the solar panel power bus.

Since the controller was designed, for the most part, with TTL elements, the power consumption is between 4 and 6 watts depending upon internal states and operating mode. However, this is actually only a penalty of 0.2% in system efficiency. The power consumption would be reduced if the TTL elements were replaced with CMOS logic elements, which are now gaining acceptance in flight applications.

A basic block diagram of the controller is shown in Figure 12A and 12B. As can be seen in the figure, the 16 bits that comprise the command word and the strobe pulse are received by command isolators. The isolators employ photo-couplers to obtain the required isolation between command return and PPU ground. The photo-coupler drivers that operate from the TTL input lines use an isolated supply for bias power. As the 16 bits leave the isolators, they are basically separated into two separate buses. Bits 1 through 12 form a value bus, and bits 13 through 16 form an address bus. These buses go to the eight storage registers where the value bits appear on the parallel inputs and the address bits are received by the address decode logic. The register load command is generated by logic that uses the strobe pulse and the output from the input power bus under-voltage detector to either load or clear the registers. The load command will only load the register

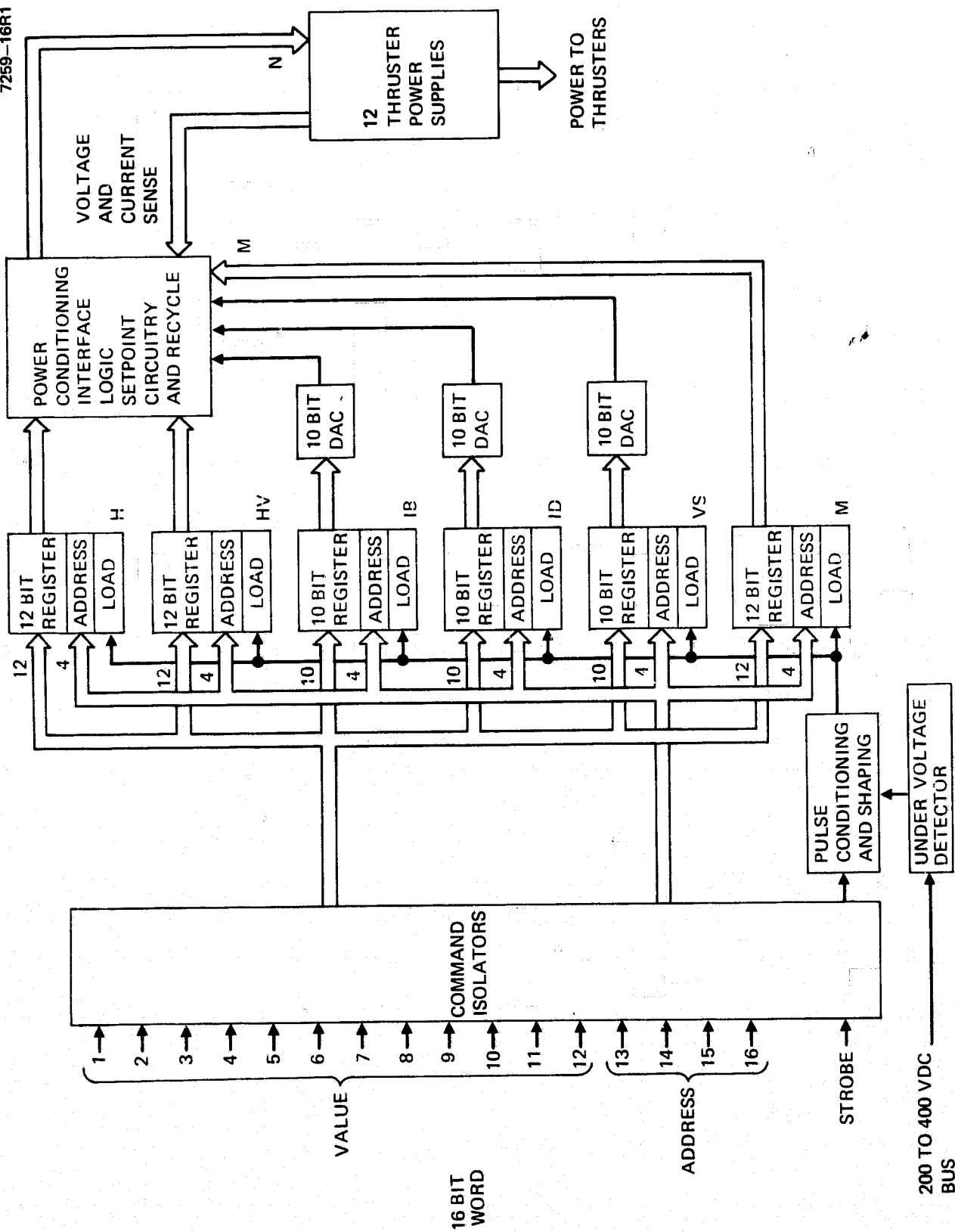


Figure 12A. Command interface and digital control block diagram.

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whose address bits decode correctly. The output of the registers H and HV goes to logic that determines the on/off conditions and selects the operating setpoints for the supplies in the TVBB. Registers IB, MB, VS, and IBO operate D/A converters which furnish various closed loop references or high accuracy supply control. The bits in register M determine which automatic function will be allowed to occur during thruster operation. The role played by the current-level detectors, and the recycle logic and timing will be examined in the portion of this report that covers the automatic functions.

A command dictionary was developed to aid in communicating with the controller. The control option word sets the automatic functions that are desired. The bits of this word are stored in the M register. The beam current reference word is stored in the register labeled IB. The bits in the IB register are converted by a 10-bit D/A converter and become the reference for the main vaporizer when the vaporizer is in closed-loop control. The discharge current, screen voltage, and magnetic baffle current reference words are stored in registers ID, VS, and MB respectively. These words are converted by D/A converters to become the references for the discharge, screen, and magnetic baffle supplies. The operating setpoints of the heater and vaporizer supplies are selected by a word that is stored in register H. A single command word selects the setpoints for the keeper supplies, provides on/off control of the magnetic baffle, discharge, and screen supplies, and sets the closed loop reference of the neutralizer keeper supply. Register HV stores this command word. The last item is the bus overload current reference word, which is stored in register IBO. The bits in register IBO are converted by a D/A converter to form the bus overload current reference.

From the above discussion, each of the 12 supplies in the TVBB has independent command capability. This gives the TVBB a great deal of operational flexibility. It is possible to vary any one supply and determine what effect the variation of that supply has upon thruster behavior. Even the heater and vaporizer supplies, which are normally

off or in closed-loop control, have three operating setpoints, one of which is variable. Three supplies whose operating setpoints are critical to proper thruster operation (i.e. the screen, discharge, and magnetic baffle supplies) are controlled by the outputs of D/A converters. This provides a high degree of accuracy and flexibility in determining their operating values. Also, the ability to select which automatic functions to employ during operation gives the operator a great deal of flexibility when operating this system.

The desired automatic functions are selected by setting bits to 1 in the control option word. The bits in the control option word are stored in the M register and are generally used in a manner similar to that shown in Figure 13. For example, when bit 1 is set to 1, the neutralizer cathode heater will automatically turn off when the neutralizer keeper supply is commanded on and keeper current is established. Likewise, when bit 2 is set to 1, the main cathode heater will automatically turn off when the discharge supply is commanded on and discharge current is established.

The three vaporizers can be transferred to closed-loop control automatically, depending upon the states of bits in the control option word and the status of certain power supplies. The neutralizer vaporizer will go to closed-loop control when bit 3 is a 1, and the neutralizer keeper supply is commanded on and drawing current. Bit 4 being a 1 will allow the main vaporizer to transfer to closed-loop control when the screen and accel supplies are commanded on (providing the discharge supply is commanded on and current is established). When bit 9 is a 1, the cathode vaporizer will transfer to closed-loop control when the discharge supply is commanded on and provides current.

The recycle enable (bit 12) in the control option word allows the recycle logic and timing circuitry to operate when a screen overload trip occurs or the input bus current exceeds the bus overload current reference. The timing diagram that shows the various events that occur during a recycle is given in Figure 14. As can be seen in Figure 14, the screen and accel supplies will be turned off for the duration of

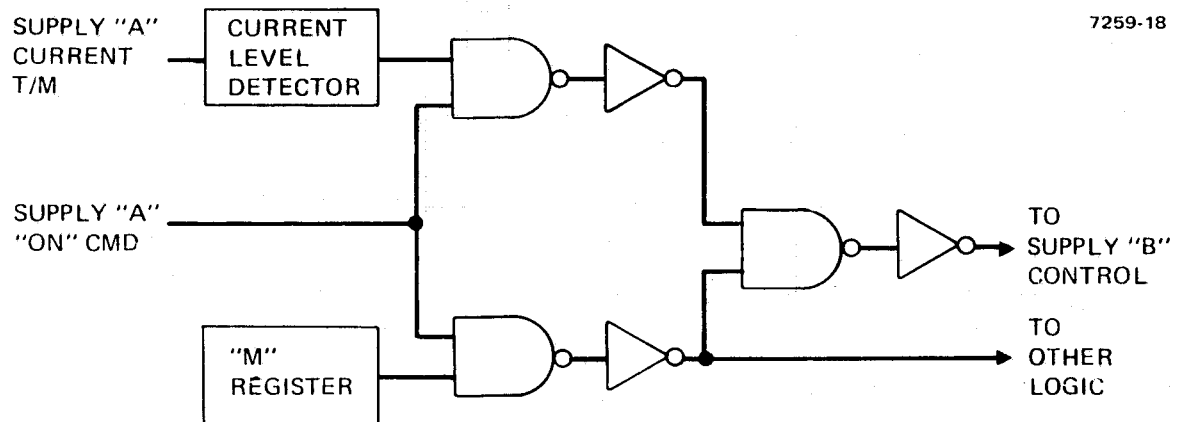


Figure 13. Automatic function block diagram.

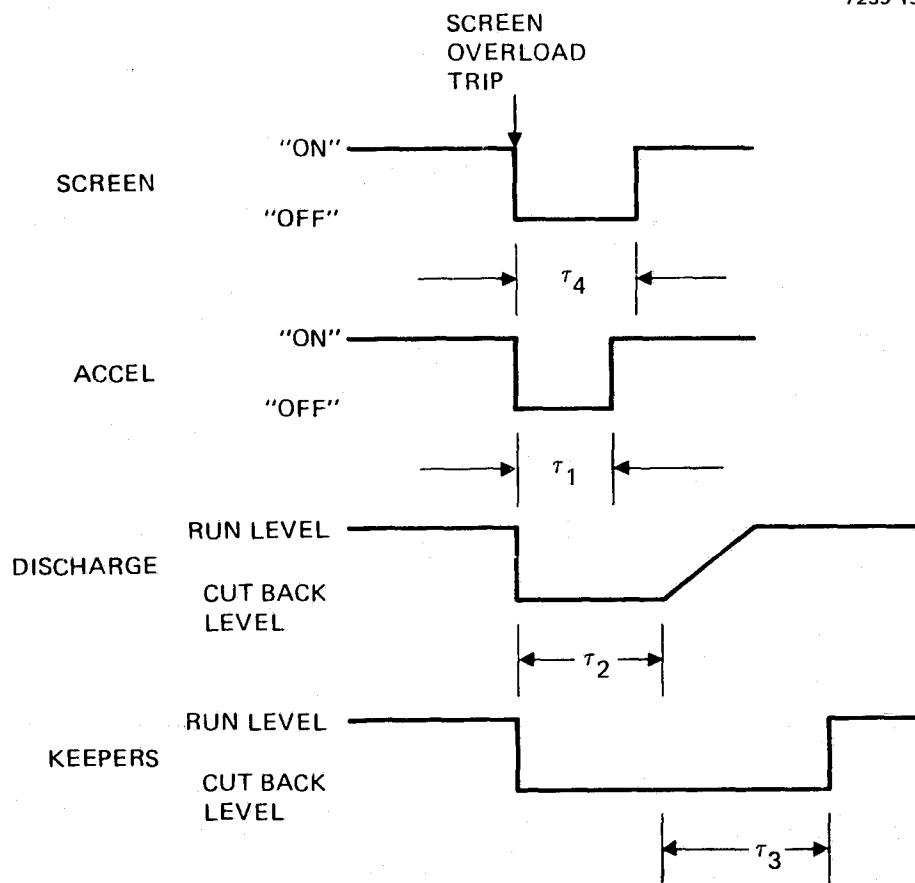


Figure 14. Recycle timing diagram.

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τ_4 and τ_1 , respectively, the discharge supply will be cut back for the internal of τ_2 , and the keepers, depending on the status of bits 10 and 11 in the control option word, will cut back for the duration of τ_2 plus τ_3 .

The trip rate override enable control option word, bit 7, will prevent the trip rate counter from turning off the screen and accel supplies should a specified trip rate be exceeded.

The low mode detector enable allows circuitry in the controller to determine if the thruster is operating in a low mode. It does this by sensing the accel current and will turn off the main vaporizer supply if an upper current limit is reached. The main vaporizer supply will remain off until the accel current is reduced to a normal value.

As previously mentioned, when the proper bits in the control option word are selected and certain supply on conditions are satisfied, the vaporizer supplies transfer to closed-loop control. Figure 15 shows the basic configuration of the vaporizer supply control circuitry. The automatic function logic selects the amplifier inside the HA-2400 programmable amplifier that is the error amplifier for the loop. In the case of the main vaporizer, the reference is generated by a D/A converter and the telemetry is of the beam current. The neutralizer vaporizer error amplifier obtains its reference from another HA-2400 that has four possible setpoints and uses the neutralizer keeper voltage telemetry. The error amplifier for the cathode vaporizer uses a fixed reference and the discharge voltage telemetry. The gain of the amplifiers is adjusted to obtain loop stability with an acceptable amount of closed-loop error.

The interfaces between the controller and the power supplies in the power portion of the TVBB can be classified into two types - digital and analog. The output portions of these interfaces are shown in Figure 16. The digital signals that are used for on/off and reset control use a low-power TTL gate and a 30- Ω terminating resistor. The levels of these signals are the standard TTL 0 and 1 logic states.

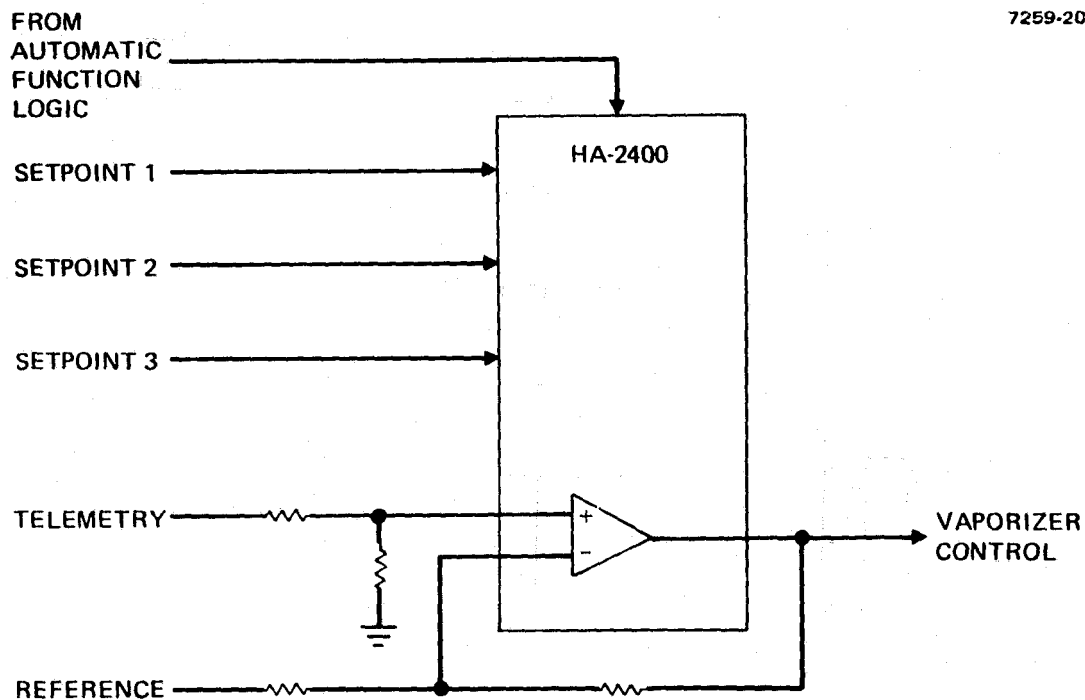


Figure 15. Closed-loop control block diagram.

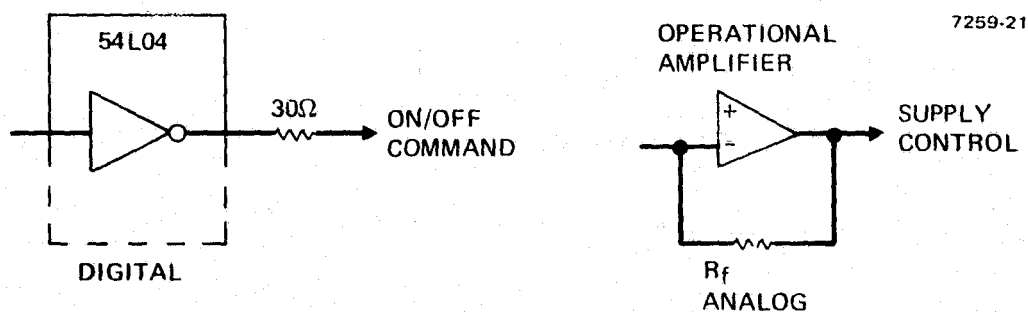


Figure 16. Supply interfaces.

The analog signals vary between zero and +5 V dc and cause the power supplies they control to vary between zero and full output. These circuits were standardized to minimize any interface problems that might arise during integration of the controller with the rest of the TVBB.

A telemetry encoder was designed to be used in conjunction with a digital display unit. The encoder selects one of the 19 channels of analog telemetry from the telemetry isolators and converts it to digital data. The channel to be converted is determined by the digital display unit via five address lines.

The address lines are decoded to close an FET switch which connects the requested telemetry channel to a A/D converter. The A/D converter receives the input telemetry from the multiplexer and the acquired signal from the digital display unit. A successive approximation register, with the aid of a comparator and a D/A converter, converts the analog telemetry to digital data. The register output is buffered and sent to the digital display unit.

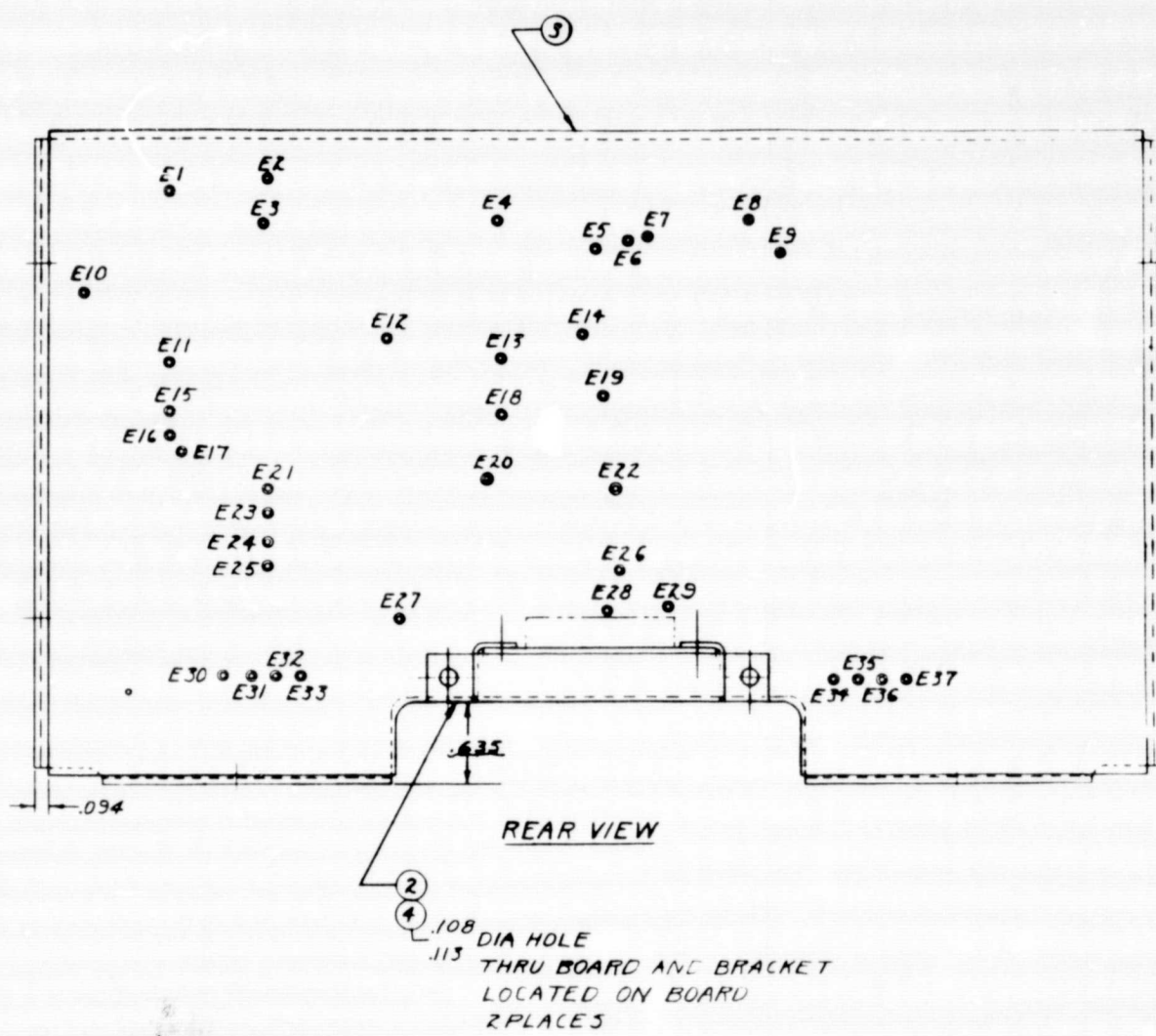
The technique used to package the controller was to bond a printed circuit board to an aluminum bracket and mount the components to the circuit board through the aluminum bracket. This is shown in Figure 17. The aluminum bracket gives mechanical strength to the circuit board and acts as a heat sink for the electrical components. The ten circuit cards that comprise the controller were combined with certain power supply control cards into a card nest which is shown in Figure 18.

Three pieces of auxiliary equipment were supplied to provide the computer and spacecraft interfaces required to allow checkout and operation of the TVBB. The command simulator provides the 16-bit parallel-strobed command words normally furnished by the computer. The 16 bits are determined by a row of 16 panel toggle switches which are set to a 1 or 0 position, and a pushbutton switch activates the strobe. The 56-Vrms, 2.4-kHz square-wave power that would normally be provided by the spacecraft power subsystem is furnished by a 2.4-kHz supply. To display the data, a digital display unit was also provided.

CARD 11
FRONT VIEW

REAR VIEW FRAME

2



Circuit card assembly.

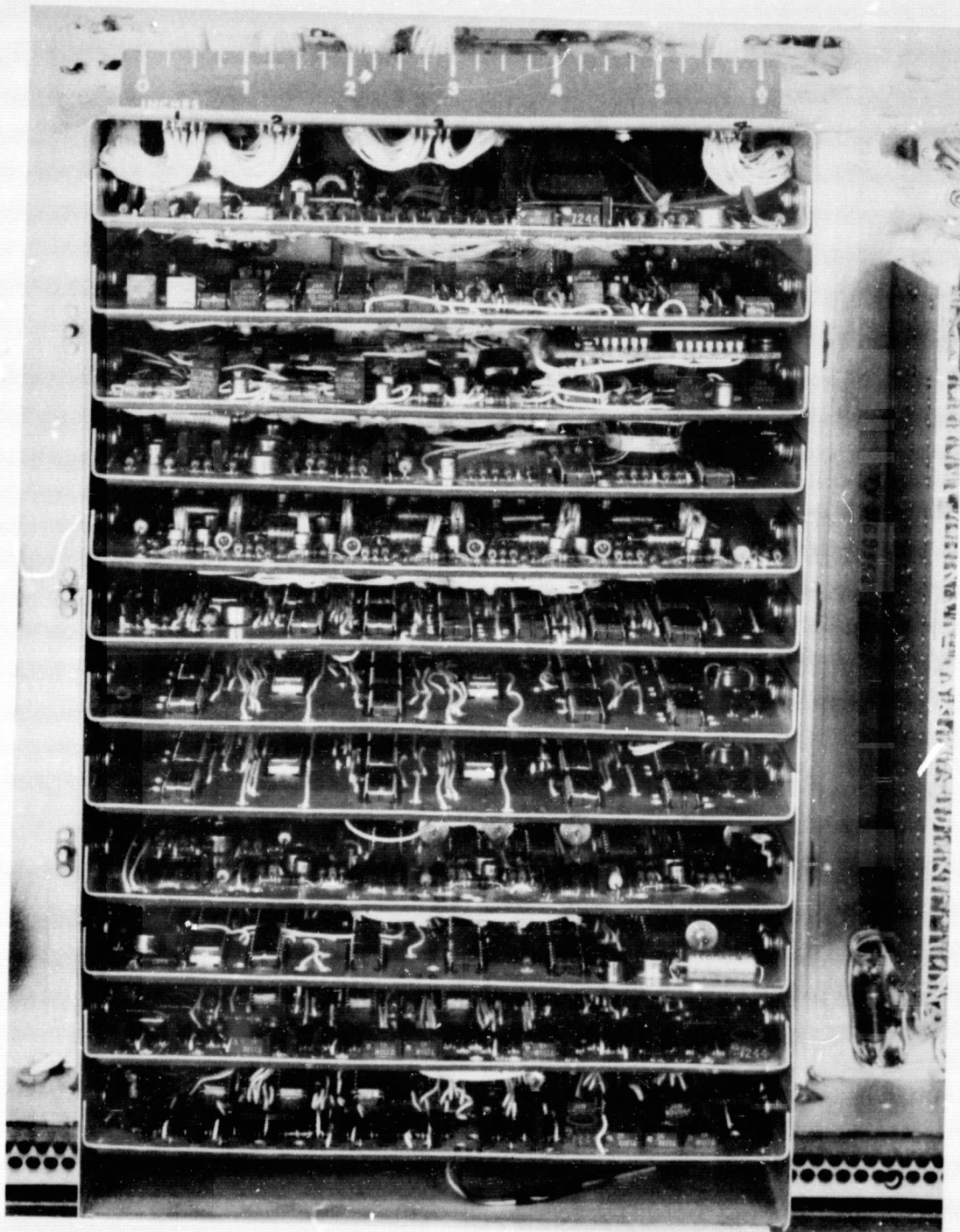


Figure 18. Control module card nest.

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MECHANICAL DESIGN

The TVBB power processor delivered to LeRC at the conclusion of the development program is shown in Figures 19 and 20. Figure 19 shows the component (back) side of the processor panel with the EMC cover removed. The internal harness seen in this view carries low-level control, telemetry, and digital timing signals. The power harness for both input and output power is routed in a closed conduit channel which forms the perimeter of the structure. This approach of separating high-power and low-power harnesses proved highly effective in controlling internal noise interactions.

Magnetic components (transformers, magnetic amplifiers and chokes) are mounted directly to module plates providing an effective thermal path and simplifying the structural tie-down. As shown by the photograph, modular implementation of the screen supply has led to reasonably homogeneous sizing of the electrical components.

The physical dimensions (with the EMC cover in place) are 62.2 x 136.9 x 11.43 cm. The system consists of an assembly of eleven module plates mounted on an egg-crate type structure made of 6061T4 aluminum. Three basic module plate sizes are used: seven are 24.1 x 29.9 cm, three are 20.3 x 31.1 cm, and one is 31.1 x 44.5 cm. Each module plate is easily removed from the front after disconnecting the harness connectors on the rear side.

Figure 20 shows the thermal radiating side of the power processor. A low thermal density philosophy has been used throughout this system. Each module plate is designed to be thermally self-sufficient. The design is based upon single-side radiation and requires a minimum amount of conduction to the structure or between modules. The thermal loading is spread on each plate in order to minimize hot spots and provides a minimum of thermal gradients, thereby producing minimum component stress. The surface is treated with a thermal control paint with an effective emittance of 0.84 and sized such that the nominal upper temperature of any one module base plate will not exceed 50°C worst case when radiating to deep space.

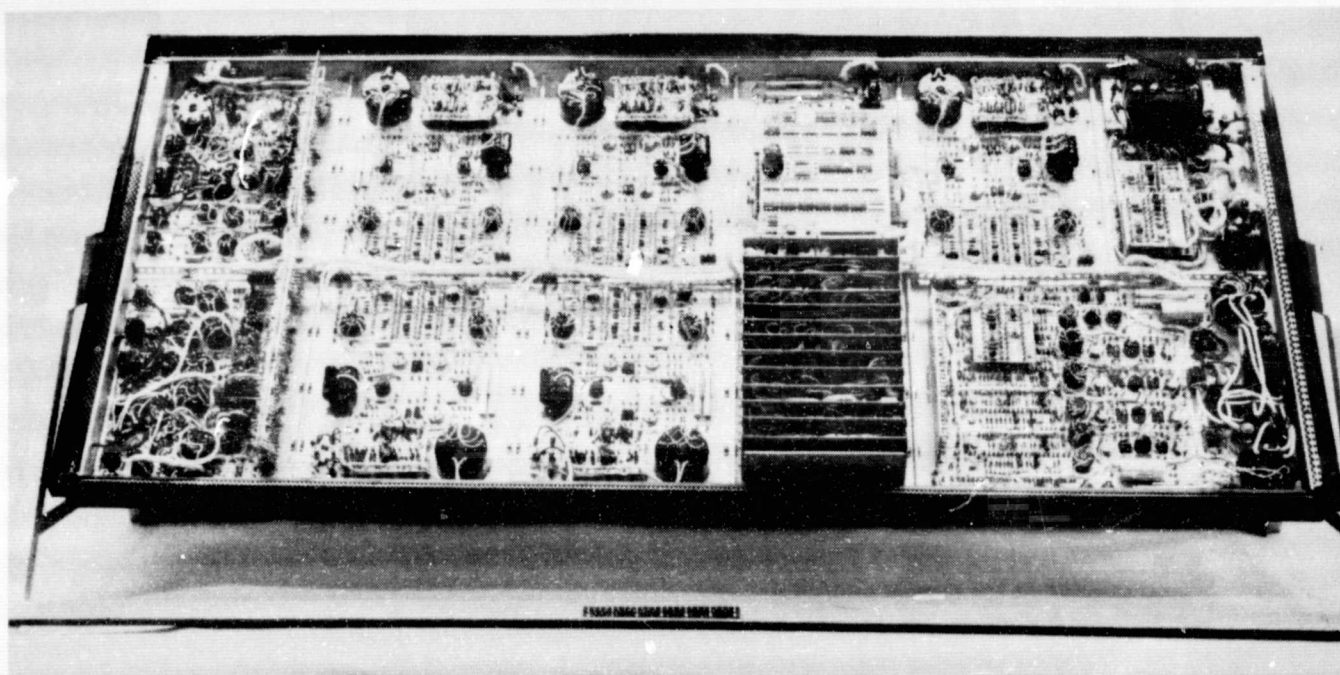
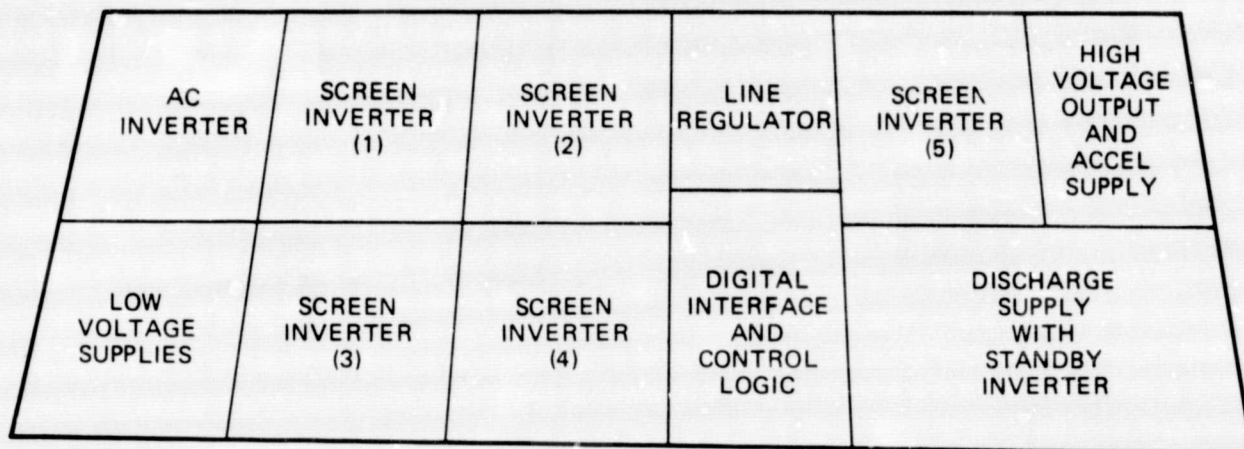


Figure 19. 30 cm thruster thermal-vacuum breadboard power processor (component side without EMC cover).

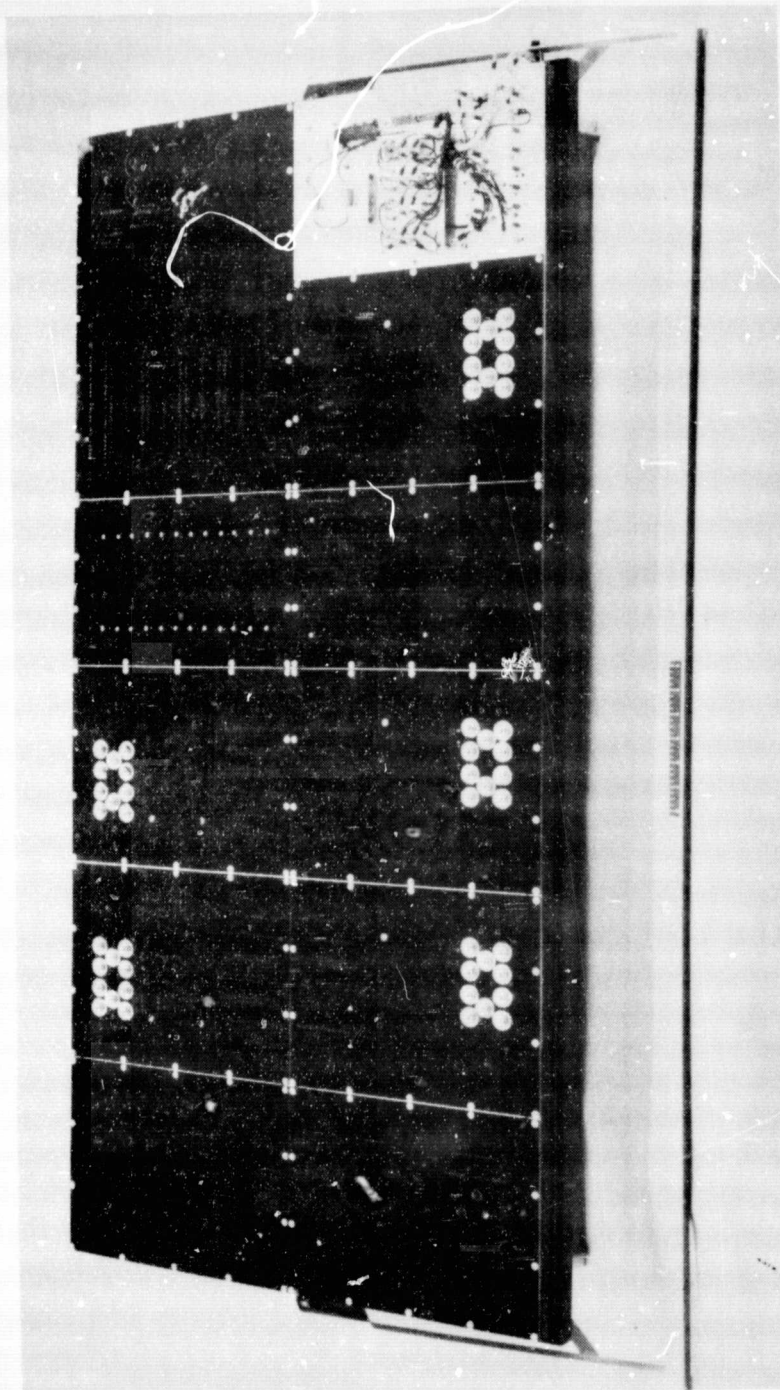


Figure 20. 30 cm thruster thermal-vacuum breadboard power processor (thermal radiation side).

A summary of the power processor masses attributable to various power, control, and structural items is given in Table 3. It should be noted that in this design the electrical component mass of 15.6 kg is approximately one-half of the total power processor mass of 32.3 kg.

Table 3. 30-cm Thruster Power Processor Mass Summary

Unit	Electrical Component Mass (kg)	Module ² Mass (kg)
Screen inverters (5) ¹	5.255	6.685
Discharge inverter ¹	3.259	3.879
Accelerator w/output filters	1.401	2.556
Line regulator	0.333	0.742
Low voltage inverter w/heater supplies	3.482	4.327
Telemetry isolation/buffer	0.191	0.616
Digital interface card	0.099	0.353
Control module assembly	1.619	3.509
Frame and internal harness	-	7.945
Back cover	-	1.643
TOTALS	15.639	32.255
	(34.45 lb)	(71.05 lb)
¹ Includes 1 standby inverter for redundancy.		
² Including weight of conformal coating.		

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TESTING

The PPU has undergone testing at Hughes and at LeRC. Testing at Hughes has included static load tests to establish detailed supply characteristics, system electrical performance, and the adequacy of the design to withstand an extensive variety of supply and intersupply shorted conditions. Limited thruster testing at Hughes near the end

of the program, prior to hardware delivery, was conducted to assess general compatibility of the power processor with the ion thruster. It had been decided earlier that the values of several of the power processor's adjustable features (setpoint levels, control loop gains, and sequencing time constants) would be finalized during thruster integration tests at LeRC immediately following delivery of the hardware.

Static Load Performance Test

Much of the static load testing conducted during both the circuit development and the system evaluation phases of the program was directed toward assuring that, under all possible steady-state and transient loading conditions, the power circuit component stresses remained limited to predetermined levels consistent with reliable, long-term operation of an ion thruster. Concerted effort was made during this testing, through the use of dynamic repetitively-switched loading, synchronized with the power switching waveforms, to produce any set of conditions which could lead to circuit failure. Each of the power supplies was shorted to its return line. In addition, the discharge supply was shorted to the screen supply and PPU return, and the screen supply was shorted to the acc supply and PPU return. By the end of the final system testing, it was concluded that no load-induced circuit failure modes existed in the implemented circuitry.

Results of power processor efficiency testing are summarized in Figure 21 and Table 4. The tests were conducted using static loads to simulate the thruster's load impedances. During the taking of the data, individual power-supply output voltage and current levels were scaled as a function of the screen supply current in a manner consistent with actual thruster operational requirements over the indicated throttling range⁷. To achieve the high system efficiencies reported here, between 91.5% and 91.91 at nominal rated load, requires that a substantial portion of the total power be conditioned by circuitry which exceeds this value, in order to offset disproportional losses in the lower-efficiency heater/keeper supplies and in the DIU. Values of

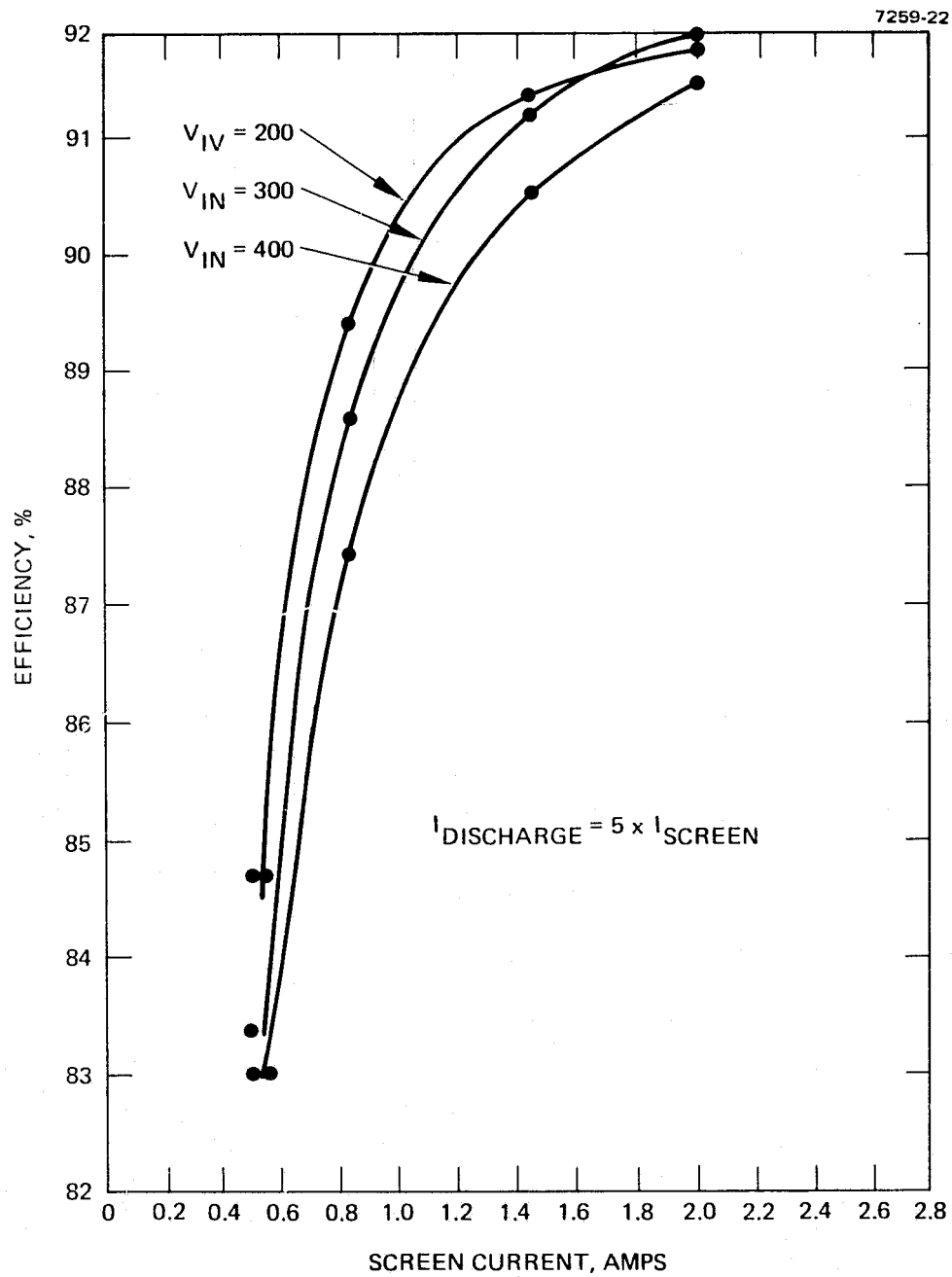


Figure 21. 30 cm thruster TVEB power processor system efficiency.

Table 4. 30-cm Thruster TVBB Power Processor
System Efficiencies at Discrete
Screen Supply Currents

Screen Output Current \ Input Line	200 V	300 V	400 V
2.0 A	91.8%	91.9%	91.5%
1.45 A	91.4%	91.2%	90.5%
0.85 A	89.4%	88.6%	87.5%
0.50 A	84.7%	83.4%	83.0%

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efficiencies achieved by the screen and discharge supplies are 95% and 92%, respectively.

From the data presented, it is apparent that the system's efficiency is relatively insensitive to the 2:1 input line variation. At a system operating point corresponding to a screen current of 2 A, the efficiency differential is 0.4% and increases to only 1.7% at 0.5A.

Hughes Integration Test

The thruster compatibility test at Hughes employed an experimental 30-cm ion thruster which had been configured to simulate, electrically, the properties of the engineering model thruster. This test consumed three days including setup and integration into the thruster test facility of the power processor and associated command and data-handling electronics. In general, the results of this first test of the newly implemented power processor were encouraging. Thruster startup and steady-state operation at beam current levels of approximately 1.5 A were achieved repeatedly. During this period, circuit operation of the power conditioning, control, and data-conversion portions of the power processor were systematically monitored to detect any potential anomalous

behavior or adverse component stresses during natural or induced transient overload conditions. When the thruster operational state was raised to near the upper nominal beam current level of 2 A, the dc screen supply output current was found to have a large oscillatory ac component which made long-term steady-state operation difficult. Subsequent addition of output filter dissipative damping improved the overall system compatibility, and allowed the taking of data from which a new filter, with a resonant frequency below the regulation loop break frequency, was designed. (The approach provides the necessary damping without additional dissipation.) Following conclusion of the testing, the modified screen filter was incorporated in the power processor, and the unit was retested and documented on static loads before shipment to LeRC.

NASA-LeRC Integration Test

Initial unit testing at LeRC, supported by Hughes personnel from the development program, was accomplished in four phases during a period of two weeks. The testing began with a preliminary postshipment checkout-indoctrination test and culminated with a full-up thruster operational test with the PPU in a thermal vacuum environment. Two interim tests - a thermal-vacuum static load test and a thruster integration test with the PPU in ambient - were conducted to establish the unit's environmental readiness and to provide an opportunity to select and install the desired control system parameter values. A detailed account is given in Appendix A.

As the tests progressed, two failures occurred in the PPU. The first was caused by an improper system grounding connection and was quickly rectified. The second resulted from the ambient plasma bridging two exposed commutating diodes attached across the 200 to 400 V input bus which caused the current level in the discharge supply's in-line fuses to be exceeded. The fuses were replaced and the diodes covered with a resin and no further problems were encountered.

Testing at LeRC clearly demonstrated the adequacy of the TVBB electrical and thermal design. Successful operation of the PPU at rated power under controlled thermal-vacuum conditions in the same vacuum chamber with the ion thruster is also considered a significant accomplishment.

CONCLUSIONS AND RECOMMENDATIONS

A 30-cm ion thruster thermal-vacuum power processor unit employing a transistorized bridge inverter power stage had been successfully developed and tested. The unit achieved an electrical efficiency of $91.7\% \pm 0.2\%$ at its nominal power rating over an input line variation of 200 to 400 V dc with a total electrical component weight of 15.64 kg (34.45 lb).

Reliable and efficient circuit operation at bus voltage levels up to 400 V proved to be the major problem encountered on the development program because of the limited number of fast-switching power transistors available with adequate voltage-breakdown margins. The problem was ultimately solved by taking the best device available and devising an innovative drive-modulation scheme which not only provided unfailingly precise stress control but also improved system efficiency. At this time, however, it is concluded that any future development effort based on the TVBB concept and destined for flight qualifications should consider lowering the 2:1 input bus voltage variation to the range of 150 to 300 V dc.

A detailed review of the system configuration and methods of circuit implementation used, together with a survey of existing materials and components, indicates that substantial efficiency and component weight improvements can be realized -- without the need for any new circuit or component technological development. System efficiency of 93% (at nominal load) and component weight projections of 12.7 kg (28 lb) appear achievable with only minor modifications of the baseline TVBB design.

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APPENDIX A

NASA-LeRC INTEGRATION TEST

On July 4, 1975, the TVBB was integrated in ambient to the Hughes built dummy load. Most functions, including all those essential for thruster operation and PPU protection, were verified. Following this, a LeRC-built interface box which provided for more convenient command control was checked out. The interface box was then integrated with the PPU and the dummy load successfully and was used in all subsequent tests.

The PPU was then connected to a thruster. After a quick startup, wherein the PPU performed as expected, beam current was obtained. Many recycles and outages of the thruster occurred, which in the opinion of LeRC personnel were primarily a function of thruster-induced conditions, such as condensation, etc. The beam current was raised and approximately 15 minutes after the beam current had been turned on, reached 2.0 amperes.

Shortly after this condition was obtained, a visible flash occurred. The flash and subsequent smoking occurred in the region of the control cards. The PPU was immediately powered down and an investigation begun.

Several components were found to have been damaged; a complete list is given in Table A-1. During the repair effort the control cards were removed and replaced many times, and it is possible that some of the components listed in Table A-1 were damaged during this repair effort.

A dummy load test was then run. At that time, however, no clear cause of the initial failure had been identified.

An extensive diagnostic and failure modes and effects analysis was carried out and it was discovered that the zener clamps between the PPU common and PPU chassis common had inadvertently not been connected. It was apparent that this condition had existed with the delivered hardware and during the first thruster integration tests at HRL.

Table A-I

Failure/Anomaly	Probable Cause	Solution
<p>I. Several Component Failures</p> <p>A. Line Regulator</p> <ol style="list-style-type: none"> 1) Series Switching Power Transistor 2) Driver Transistor 3) Driver Diode 4) Base Emitter Resistor on Power Transistor <p>B. Low Voltage Inverter</p> <ol style="list-style-type: none"> 1) Power Switching Transistor 2) Driver Transistor <p>C. Control Module</p> <ol style="list-style-type: none"> 1) Inverter Gate 2) Resistor 3) Op. Amps. and Resistors <p>II. Overheated Diodes (not Failed)</p> <p>III. OP-AMP in Screen Control System</p> <p>IV. Neut. Keeper OFF Common Falsely Generated</p> <p>V. Failure of buses in the two discharge inverters</p>	<p>Conditions caused by failure to clamp PPU common to PPU chassis with zener</p> <p>Damaged during rework of Item II</p> <p>Absence of appropriate noise suppression capacitors</p> <p>Overheating of the fuses caused by poor thermal paths and an excessive current load caused by a plasma leakage path</p>	<p>Connect zeners</p> <p>Replace Op-Amp</p> <p>Capacitors added</p> <p>Improve thermal conduction and shield discharge diodes to prevent plasma leakage.</p>

The absence of the zener clamps was a very likely cause for the chain of failures observed (a view supported by subsequent events). This failure mode would not be observed on resistive load tests as these tests do not properly simulate the totality of dynamic behavior of thruster neutralization processes and hence would not produce the range of floating voltages on the control system experienced during thruster operation (with zeners removed).

Following connection of the zeners, a dummy load test was performed successfully. The thruster was then wired to the PPU and an integration test was performed. Most functions were demonstrated successfully including steady state operation of the thruster at 2.19 amperes, many recycles, and operation over an extensive throttling range (0.8 - 2.19 A). In order to account for a 3-volt drop in the discharge circuit, caused primarily by the many connectors placed in this system for experimental convenience, the discharge voltage setpoint at the PPU output was increased to approximately 40 volts. One anomaly was noted in PPU operation in that some indication was given that a false neutralizer command was being sent.

The PPU was prepared for a thermal vacuum test on a dummy load and certain changes, such as covering the high voltage output leads, required in the thruster integration test, were not made in order to expedite the first thermal vacuum test. Two diodes which had been overheated slightly were discovered. Although the diodes were still functional, they were replaced.

The PPU was placed in the 3-meter (10-ft) bell jar of the LeRC facility. A checkout test was performed and the PPU was operational except for a difficulty in the screen supply, which was traced to a damaged operational amplifier in the screen supply control circuit. It was felt that this amplifier had been damaged during the replacement of the two diodes previously mentioned. Following replacement of the amplifier, a successful ambient checkout of the PPU was completed.

A PPU bake-out procedure was then undertaken. The location of the thermocouples used are shown in Figure A-1. Only one thermocouple was included on the circuit side, No. 12. This T/C was located on the

COMPONENT SIDE

7259-24

⑥	③	④ 12	⑧		⑩
A1	A2	A3	A4	A5	A6
A7	A8	A9	A10	A11 ⑨	
⑤	②	①	⑦		

RADIATING SIDE (TC SIDE)

⑤		①	⑦		

Figure A-1. Thermocouple locations.

screen inverter rectifier diode card. The bake-out schedule, showing time variation of PPU baseplate temperature and facility pressure, was a compromise between most conservative approach and available time constraints and is shown in Figure A-2.

The PPU was then turned on while attached to dummy load and after some adjustments of load resistance configuration was allowed to reach thermal equilibrium. This test proceeded without incident and a decision was made to run the PPU overnight in an unattended mode. This test ran for a total of 18 hours and 20 minutes with 18 hours at full (nominal) power. The values of power supply outputs are given in Table A-2. The final values of the temperatures are shown in Table A-3. (These temperatures were estimated to be accurate to about 10°F .) It is interesting to note that due to the thermal design and low dissipated power of this PPU, the observed operating temperatures in thermal vacuum were lower than during ambient (80°F) tests.

This test was then shut down. Epoxy and other plasma shielding was applied to exposed high-voltage terminals to prohibit interaction with any ambient plasma during thruster tests. Also, in order to address possible noise problems, approximately 12 noise suppression capacitors were added into the control system of the power processor. An overnight bake-out was then initiated, and the bakeout schedule is shown in Figure A-2.

A thruster/PPU test was then attempted. Preheat and ignition of the plasma loads proceeded without incident. It was noted that the discharge plasma was very unstable early in the heat phase. This was attributed to the state of the thruster which in the three previous tests had large amounts of mercury delivered to the thruster without any discharge ignition. After the discharge had become stable, high voltage was applied. For the duration of the test, the high voltage recycled much more often than normal, although in the latter stages the beam, which reached 1.3 A, would stay on for periods up to 30 seconds to 1 minute. The test terminated suddenly when all power into the PPU was shut down.

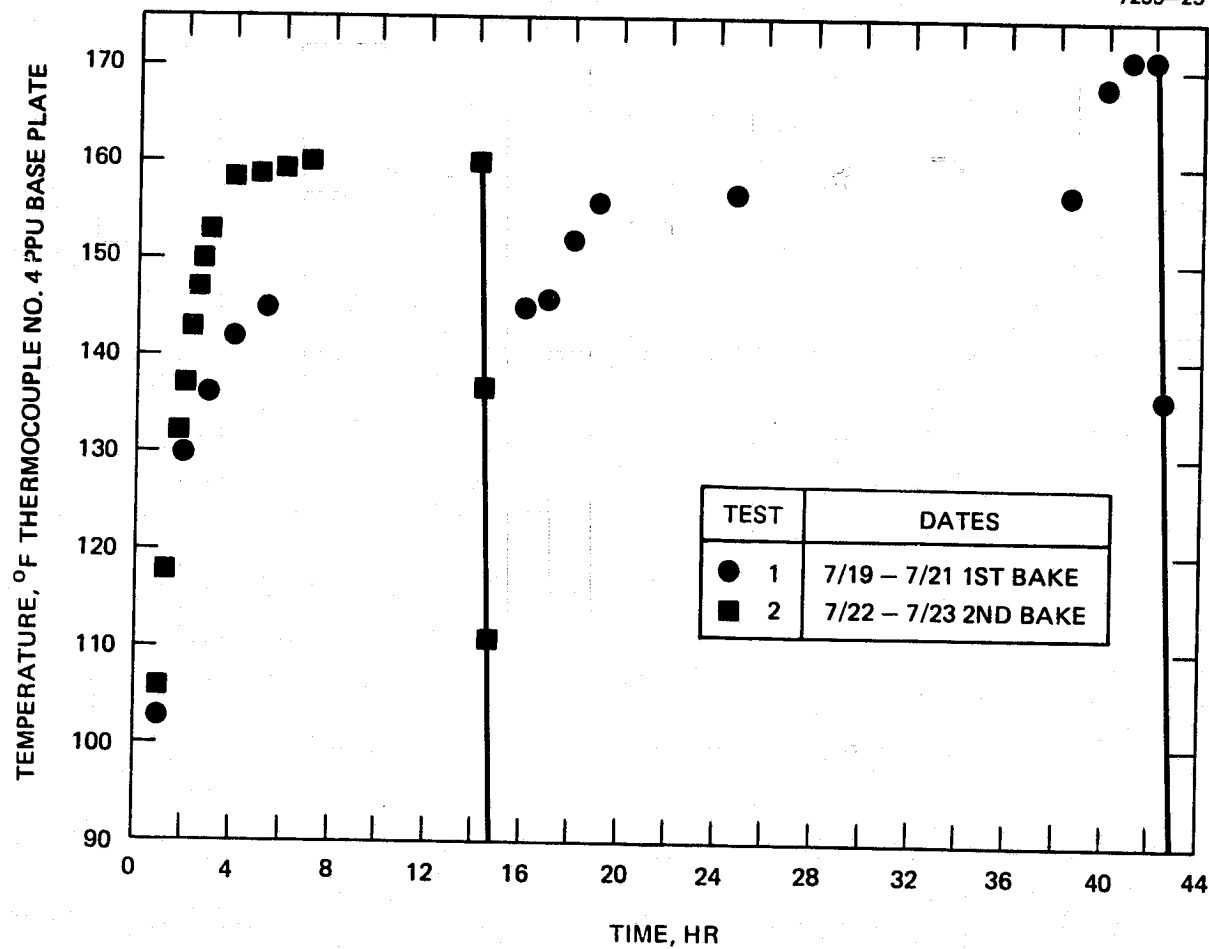


Figure A-2A. Outgassing temperature schedule.

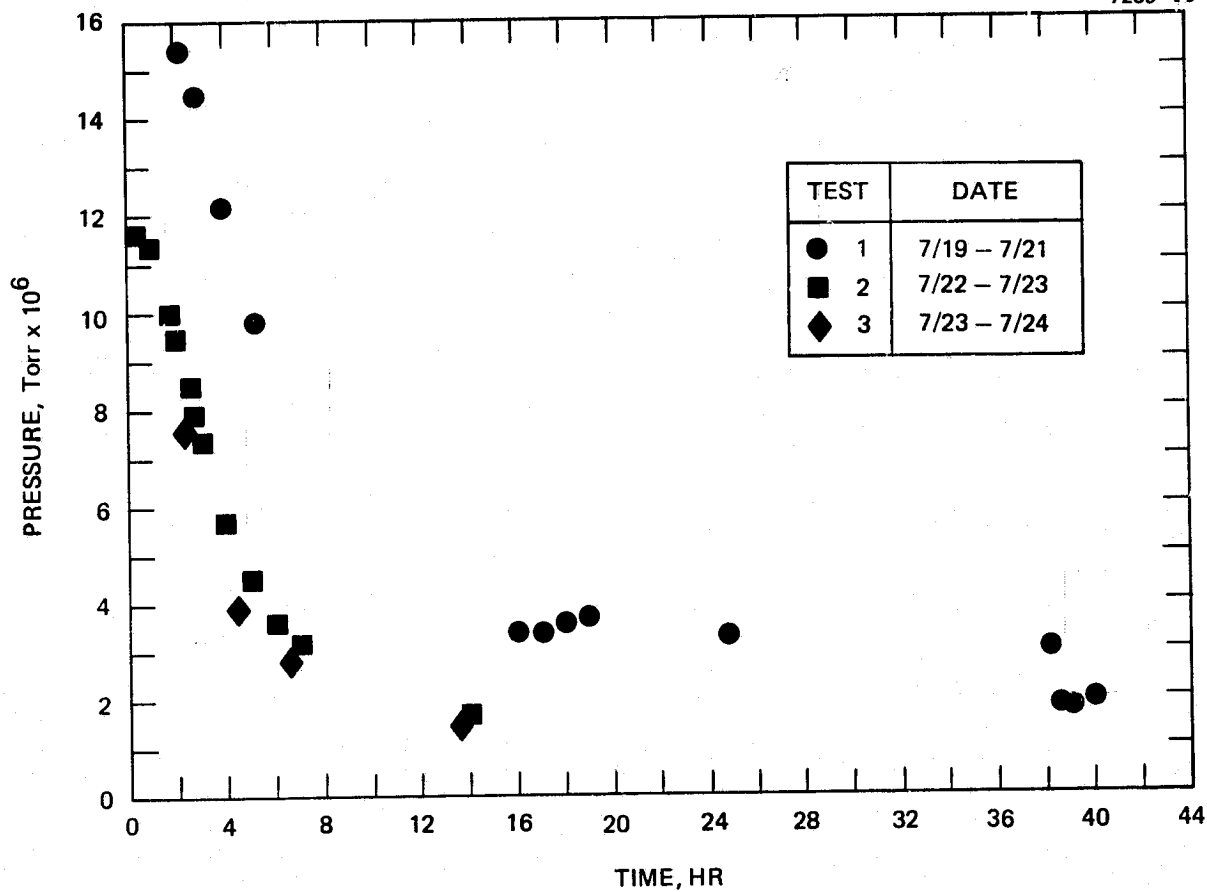


Figure A-2B. Facility pressure versus time during outgassing schedule.

Table A-2. PPU Outputs During 18-Hour
Thermal Vacuum Dummy
Load Test

Channel	Output	TLM	Value
1	Screen voltage	3.87	1190 V
2	Screen current	3.87	1.96 A
3	Accel voltage	2.57	520 V
4	Accel current	0.315	3.7 mA
5	Discharge voltage	3.87	38.7 V
6	Discharge current	2.50	9.9 A
7	Main isol current	2.90	1.20 A
8	Cath isol current	4.53	1.77 A
9	Cath htr current	0.31	0 A
10	Cath vap current	5.01	2.1 A
11	Neut htr current	0.15	0 A
12	Neut vap current	3.23	1.25 A
13	Main vap current	3.88	1.5 A
14	Mag baf current	1.27	1.2 A
15	Cath kpr voltage	0.01	4.2 V
16	Cath kpr current	2.58	0.51 A
17	Neut kpr current	2.58	2.05 A
18	Neut kpr voltage	0.01	17.5 V

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Table A-3. Final Temperature After 18-Hour TV-PPP
Dummy Load Test

Thermocouple	Temperature, °F
1	59
2	63
3	61
4	59
5	37
6	40
7	34
8	21
9	52
10	17
12	75
Temperatures estimated to be low by ≈10°F. Estimated relative accuracy ≈±5°F.	

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An initial checkout indicated all supplies except discharge and screen were functional. It was observed that the discharge supply would not deliver current (to a dummy load) and the screen supply was not tested.

The PPU was opened to atmosphere and a check revealed that the fuses in the input leg of both the main and redundant discharge inverters had failed open. The fuses had suffered no damage evident from a visual inspection. No other component failures were discovered.

In the absence of any other component failures or anomalous behavior of the PPU or support equipment, it was assumed that the fuses failed due to overheating in the thermal vacuum environment. (The data from the TV-PPU test on dummy load revealed no evidence of overheating or

of discharge supply inverter failure.) In order to solve an overheating problem, the fuses were thermally bonded to the baseplate with an electrical resin. At this juncture, it was felt that long-term overheating of the fuses was the best explanation of the fuse failure.

The power supply was then subjected to bakeout No. 3 (Figure A-2), and the thruster was started again. Early in the test, some instabilities were observed, which were felt to be induced by condensation in the thruster. A beam current of 2.01 amperes was achieved, and it was noted that frequency recycles would occur if the emission current exceeded about 8.5 A. An oscilloscope reading revealed that there was peak-to-peak oscillations of at least 12 amperes in the emission current at frequencies between 10 and 20 kHz. After about one-half hour at 2.0 ampere beam operation, the thruster was shut down. A 3-m Henry choke was added to the output of the power supply (this value had been determined as optimal on tests with other thrusters and power supplies). Following this, a very smooth startup was performed and the discharge current oscillations were reduced to less than 1 ampere peak-to-peak. The thruster ran very stably at 2.0 amperes for about 1.5 hours at which time a failure, similar to that during the previous thruster test, occurred.

Upon opening the bell jar to atmosphere, it was determined that the two discharge inverter fuses has failed open again. Detailed inspection of the PPU revealed burn marks on the studs of the commutating diodes in both discharge inverters. The burn marks were on the ends of the studs (which are +300 V with respect to chassis) on the baseplate side of the PPU, and it was conjectured that the ambient plasma allowed a current path to exist, which led to overheating of the fuses. It was not clear if this current path through the plasma was continuous (e.g., similar to a glow discharge) or abrupt, or both.

The fuses were replaced and the diode studs were covered with a resin. To better assure mechanical integrity of the resin, a special ambient bake-out of over 2 hours at 145°F was performed followed by a normal vacuum bake-out.

The thruster (with the choke in the discharge supply) was then restarted. A successful thruster test was then performed where the PPU operated in vacuum in a beam-on condition for 6 hours. The first 4 hours were at a beam current of 2.0 amperes while during the last two hours, the thruster was throttled between 0.4 and 2.24 amperes. All control loops were successfully demonstrated. Thruster performance was measured and the discharge utilization was approximately 97 percent at a cost of 168 eV per ion.

One anomaly was noted in that difficulty in high voltage recycle was observed for discharge currents above about 9.0 amperes. This was apparently due to improper sequencing logic, which is not of the type presently recommended for the EP/PPU. The logic can be changed easily via trim pots in the PPU.

Shut down was normal and occasioned by a scheduled tank shutdown for area power system work.